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Birds & Blades: Environmentally safe spatial allocation of wind turbine structures

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Abstract

Although, it is well recognized that harnessing wind energy is highly indispensable, but collisions of birds at wind turbines has also developed simultaneously, concerning multiple bird species. With wind being strongly affected by the landscape and the behaviour of birds also being strongly influenced by the landscape, the main objective of the thesis was to understand the relevance of interactions between wind energy infrastructures and bird species from an ecological perspective of the landscape. Utilizing the carcass collision datasets of the frequently-hit bird-groups paradoxically as proxies for species presence, collision sensitive ecological distances to different land-use types were ascertained, by employing multiple techniques of species distribution modelling (SDMs), to delineate their respective collision sensitive niche employing the capabilities of machine learning algorithms. The predicted areas were specialized and highly dispersed across the federal state, with raptors showing the broadest niche and significant overlaps with the other groups. Based on estimated collision probabilities of the assessed areas (between 0 and 1), further segregations differentiated only those areas with negligible collision probabilities, <0.05, which were interpreted as the actual "no risk areas, suggesting any further planned additions of wind turbines to be suitably positioned only in these “safer” areas. Additionally, these collision probabilities were translated to strike susceptibilities, by relating them to the regional density distributions of the species as well. Summarizing, these analyses paradigmatically ascertained collision risk areas, and especially the collision sensitive distances from different land-use types to these areas, enabling the accurate guidance of future wind farm expansions in the landscape. Ultimately, formulating novel wind turbine allocation strategies to minimize avian collisions, making them as compatible as possible.

Zusammenfassung

Kollisionen von Vögeln mit Windturbinen haben sich zu einer bedenklichen Quelle für die Gefährdung besonders von Populationen seltenerer Vogelarten entwickelt. Allerdings wird im Allgemeinen auch bestätigt, dass die Nutzung der Windenergie unverzichtbar ist. Das Hauptziel dieser Arbeit war es, die Relevanz der Wechselwirkungen zu verstehen, die zwischen technischen Infrastrukturen und den von Kollisionen betroffenen Vogelarten auf der Landschaftsebene stattfinden. Da sowohl von der Landschaft beeinflusst werden. Unter Nutzung der durch gezielte Nachsuche gefundenen Opfer der am häufigsten von Kollisionen betroffenen Artengruppen paradoxerweise as als Proxy für das Vorkommen von Arten, und Durch die Anwendung verschiedener Techniken zur Modellierung der Artenverbreitung (SDMs) die "kollisionsempfindliche Nische "für jede der Vogelgruppen beschrieben. Obwohl die vorhergesagten Gebiete mit potenziellen Kollisionsrisiko insgesamt nur kleine, aber stark verteilt im ungefährdes Bundeslandes hatten. Greifvögel mit die breiteste Nische, die zudem signifikante Überlappungen mit den kollisionsempfindlichen Nischen der anderen Gruppen aufwies. Die niedrig bewerteten Gebiete weiter differenziert, die als tatsächliche „Bereiche ohne Risiko" interpretiert wurden, für weitere geplante Winkraftanlagen. Zusätzlich die jeweiligen Potentiale und Gefärdungen für Kollisionen auf der Basis der regionalen Dichteverteilungen der Arten in Brandenburg mit Ensemble-Methoden von Boosted Regression Trees wird ebenfalls bewertet. Zusammenfassend, diese Analysen paradigmatisch, sowohl die Gebiete als auch die Entfernungen zu den Grenzlinien der verschiedenen Landnutzungsformen ein höheres Risiko für die Kollision von Individuen der untersuchten Arten mit Windkraftanlagen ergibt ermitteln . Dieser Ansatz kann es möglich machen, zukünftige Windparkerweiterungen in der Landschaft im die möglichst kollisionsfreie und naturverträglicheStandorte in der Landschaft.

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Chapter I: Introduction

1.1 Transforming energy generation

1.1a Renewable energy and biodiversity: implications of transformations

Components of global change range from habitat destruction/alteration, overexploitation, pollution, climate change to species invasion. Though these drivers can produce changes in the ecosystem independently, the final fate of biodiversity is often driven by synergistic processes (Sánchez-Zapata et al. 2016). As a consequence, the resultant aftereffects are often detached from the original driver of change that may lead to unexpected shifts in the biosphere (Barnosky et al. 2012). Regardless, climate change seems to have greater prominence, leading to preeminent funding and attention, with respect to the other drivers of global change (Veríssimo et al. 2014).

Reducing greenhouse gas emissions responsible for anthropogenic climate change is the central objective of renewable energy production. Production of renewable energies has been in use for decades, e.g. hydropower infrastructure, and is complemented recently by innovative technologies, e.g. windpower and solar energy. Although renewable energy aims to provide humans a low-carbon future, the development of infrastructure aimed to produce and distribute it may have detrimental effects on biodiversity and ecosystems (Sánchez-Zapata et al. 2016).

The development, production and transportation of renewable energies have several environmental impacts, ranging from the level of populations, species, and communities up to the ecosystem level. It is highly crucial that information regarding these inevitable impacts is incorporated into the decision-making processes to formulate suitable guidelines for mitigation purposes. Given that energy consumption is all set to double itself in the coming decades, it becomes imperative to figure out ways to assess and manage trade-offs between biodiversity conservation and renewable energy generation. E.g.

Wind power generation from turbines powered by rotating blades, is increasingly becoming an emerging source of ecological impacts both at the local and regional levels (Sánchez-Zapata et al. 2016), with strong effects on avian (Tabassum et al. 2014) and aquatic species (Shuster et al. 2015) depending on generation onshore or offshore, respectively. Although turbine installations also lead to habitat loss, indirectly through species avoidance of the areas around wind energy facilities (Tabassum et al. 2014; Shuster et al. 2015), unsurprisingly, the prime threat to biodiversity arises from the collisions of birds (Carrete et al. 2009; Schaub et al. 2012; Furness et al. 2013) and bats (Peste et al. 2015) while the actual effects at their respective population levels is still less understood (Schaub et al. 2012).

Similarly, other renewable energy options have also been identified as emerging threats to biodiversity, primarily due to habitat loss, alteration and fragmentation, ultimately effecting a large number of species; e.g. solar (Turney and Fthenakis, 2011; Sánchez-Zapata et al. 2016; Gasparatos et al. 2017), bioenergy (Dauber et al. 2010; Fargione et al. 2010; Immerzeel et al. 2014; Gasparatos et al. 2017), hydropower (Poff and Zimmerman, 2010; Brown et al. 2013; King, 2013; Fearnside, 2014; Benchimol et al. 2015), geothermal (Fletcher et al. 2011; Bayer et al. 2013; Chaudhary et al. 2015) and oceanic ecosystems (Frid et al. 2012; Magagna et al. 2014; Bonar et al. 2015; REN21, 2015).

Conclusively, the respective supporting infrastructures of these resources; transmission lines other hard stand facilities, also collectively have further outreaching and extensive impacts on biodiversity and ecosystems (Sánchez-Zapata et al. 2016), in terms of additional space required, going beyond the actual space acquired by the energy infrastructure themselves (Gasparatos et al. 2017).

1.1b Wind turbines and birds: State of art

With avian collisions at wind turbine structures rapidly developing as a cause of serious conservation concern, threatening multiple bird populations, a wide variety of methods have been developed to aid the assessment of their collision risks at these structures (Masden and Cook, 2016). The methods can be broadly classified as those based on the pre-construction assessments (bird habitat use, abundance, flight behavior etc.) of the wind turbines in the development zones (Douglas et al. 2012) and post-construction assessments by fatality search operations around the sited turbines to document the actual number of collisions (Huso and Dalthorp, 2014), and lastly those that apply more theoretically to these assessments e.g. collision risk models, which predict collision probabilities (Smales et al. 2013; Eichhorn et al. 2012).

Currently available avian collision risk models each has been developed with its own purpose (Madsen and Cook, 2016) exploring different aspects of calculating collision probability, by including different components of collision, e.g. bird phenology (Tucker 1996; Band 2012a; 2012b), the configurations of the turbine (Band 2012a; 2012b), bird behavior (McAdam, 2005), their angle of approach (Holmstorm et al. 2011, Smales et al. 2013), geometry of the wind farm (Bolker et al. 2014) and co-occurrence of birds and turbines in space (Eichhorn et al. 2012). There are many arrays of such models using different approaches on these components to assess the collision risks. Although they provide likely estimates of possible collisions, they all have certain limitations that influence the model output (Madsen and Cook, 2016).

One of their greatest limitation is their assumptions based on bird presence and bird behaviors at a given development zone. E.g. In cases of models using data from vantage point survey (UFWS, 2013), where multiple observations of the number of birds using a development zone can increase the number of exposure events assessed by the model, overestimating the total number of collisions, which is supported by existing research that could not establish linear relationship between bird abundance and collision risks (De Lucas et al. 2008; Ferrer et al. 2012). Another flipside of the collision risk models are their ample requirements of data, including many input parameters related to the components involved in collision of birds and the wind turbine structures. Band (2012a; 2012b) required multiple input parameters related to both, birds and the turbines. However, data availability is often limited (Madsen and Cook, 2016) making opportunities for model validation also quite limited. In addition to these limitations, significant developments in the wind energy industries for increased energy outputs: layout of the wind farms, changes in distribution of the turbine arrays across the wind farms, increase in turbine configurations (i.e. tower height, rotor blade length; Madsen and Cook, 2016) also make it necessary for the collision risk models to be able to accommodate these developments to ensure a sufficient reliability of the output.

With advancements in the state of the art, collision risks were found to not only be associated with species-specific behaviors and turbine configurations, but with interactions among these parameters and other factors, such as topography, land-use types, weather conditions in the development zones (Smallwood et al. 2009; De Lucas et al. 2012; Schaub 2012; Marques et al. 2014) and the spatial design of the wind farms to the distribution of turbines in arrays (Ferrer et al. 2012). Studies also highlighted the importance of inclusion of these factors in the collision risk models at the individual turbine and not at the entire wind farm scale, as birds do not move randomly over an area, but follow the main wind currents over an area, which varies by topography and might vary within a wind farm (Ferrer et al. 2012). Therefore, certain locations of wind turbines within a wind farm might be very dangerous even though assessed with a relatively low density of birds crossing the area whereas other locations could be very safe even with higher densities of birds (De Lucas et al. 2012). This challenges the main assumption of wind farm assessment studies that there is a linear relationship between collision risk and bird availability at the development zones. Concentration of collision victims at few turbines in a wind farm, while other wind turbines in the same wind farm, though being superficially similar but incur no deaths, indicate that "site selection" for turbines can play the most important role in limiting the number of collision fatalities (De Lucas et al. 2012). Therefore, to further advances in collision risk modelling that effectively contribute to impact assessments, factors associated to topography, land-use types, site assessments at turbine scales become highly necessary and need to be incorporated into the collision risk models to make assumptions assisting bird survey and bird abundance data, that are found to be weakly related to mortality events at wind farm sites (De Lucas et al. 2008; Ferrer et al. 2012).

1.1c Wind turbines and birds in Germany: background, insights and mitigation measures (exclusively in the design phase)

Europe has a currently installed wind energy capacity of approximately 250 Gigawatts (GW). Countries wise contributions: Germany holds the highest stakes and contributes 62.07 GW, followed by Spain (23.97 GW), France (16.66 GW) and Italy (10.80 GW). Other European countries contribute <10 GW individually.

Since it's antecedent in Germany, i.e. 25 years back, the possible impacts of wind farms on birds have also emerged gradually as a serious cause of concern (Grünkorn et al. 2017). Although wind energy development has greatly expanded in Germany over the decades; with a total number of 5316 windfarms with an approximate number of 25,000 turbines already been installed, but only a handful of small-scale studies quantifying bird collisions at these wind turbine structures (Grünkorn et al. 2009; Dürr, 2011, Eichhorn et al. 2012; Illner, 2012; Bellebaum et al. 2013; Hötker et al. 2013; Rasran and Dürr, 2013; Rasran and Thomsen, 2013; Schreiber, 2014; Langgemach and Dürr, 2015; Weitekamp et al. 2015; Grünkorn et al. 2016).

Installation Phase	Planned (GW)	Approved (GW)	Under construction (GW)	Operational (GW)	Dismantled (GW)
Onshore			0.29	54.40	1.08
Offshore	0.01	3.99	1.46	5.93	0.01

Source: thewindpower.net

Table I: Wind turbines installed in Germany (Categorized as per type-installation phase)

During the initial years, resulting disturbances and displacements remained the main focus (Reichenbach et al. 2004) that gradually shifted towards the resulting collision risks (Hötker et al. 2013; LAG VSW, 2015; Langgemach and Dürr, 2015). Most of the research was based on systematic surveys of deadly collisions of birds with turbine structures, but also on incidental finds, that usually underestimate the number of birds being actually killed after having collided (LAG VSW, 2015). The chances of finding collision victims under the turbines is low because they remain available for a very short span of time, being quickly removed by scavengers, predators and also by humans. Therefore, the actual number of losses is appreciably higher than the number of birds actually detected. Notwithstanding, studies have tried to extrapolate carcass detections and assess effects at the population level (Korner-Nievergelt et al. 2011; Bellebaum et al. 2013; Korner-Nievergelt et al. 2013). Other studies tried to elucidate avoidance/attraction mechanisms to these humans made structures (May et al. 2015).

The current practices in the design phase prior to siting of wind farms in Germany follow the basic principle of mitigating the impacts of wind farms on bird species, especially the ones of higher conservation concern by maintaining a sufficient recommended distance between the wind turbines and their respective breeding sites and/or important roosting sites.

Moreover, as per recommendations, also the core areas with particularly higher congregations of birds are excluded from the development of wind energy infrastructure (LAG VSW, 2015). These recommendations take into account cohesive understanding of activity patterns in spaces with their higher probabilities of occurrence, in addition to their avoidance behavior, barrier effects/disturbance potentials and possible risk of collisions, notably at the pre-existing wind turbines.

The minimum distances are especially justified by the general assessment that the levels of activities are significantly higher near the nest site, which has been validated in several studies. This postulates that the risk of collision for particular species significantly increases with allocation of the proposed wind farm within this recommended distance and recommends focusing preferably on allocations beyond them (Hötker et al. 2013; LAG VSW, 2015). In some cases larger distances are recommended, e.g. along migration routes/flight corridors (Isselbächer and Isselbächer, 2001) and stopover sites for migratory birds (Köhler et al. 2014) determined through extensive flight observations comparable to the so-called ‘vantage point watches’ recommended by Scottish Natural Heritage (SNH, 2014). The prime intent behind planning prior to siting being the safeguard of populations occurring in these high-density regions functioning as source populations. These regions produce an excess of individuals that can flexibly compensate for losses in other regions with comparably lower densities, in addition to avoiding legal implications for the approval of wind farms.

Such mitigation measures during the design phase aim to minimize the inevitable impacts through design of the wind farms and micro-siting of the wind turbines (May et al. 2015). There is great opportunity for siting; to optimize wind energy generation and mitigation of unavoidable impacts simultaneously.

1.1d Germany's renewable energy policies and political objectives

With many federal states in Germany aim at doubling their currently installed capacities, by providing up to 1.5 % of their land space for the development of onshore wind energy (IWES, 2017). Brandenburg is one such sate of the country having ambitious energy strategies since 2002 (BMU, 2010). While contributing to Germany's energy revolution *("Energiewende")* targets of 40-45 % energy generation from renewables by 2025, 55-60 % by 2035 and at least 80 % by 2050 as compared to 1990 (Moeller et al. 2014), Brandenburg first laid down its renewable energy policies and economic guidelines in 2002 "The Energy Strategy 2010", calling for an initial 5 % of the total amount of primary energy generation by renewables. Surpassing the target before time, it presented "The Energy Strategy 2020" in 2008, where renewable energies played an even more important role, taking up to 20 % of the total amount of primary energy generation by 2020.

The availability of significant lignite capacities, being the countrywide unique feature of Brandenburg results in its massive net energy generation from fossil fuels (Strommix, 2010). Additionally, the federal state also meets 60-70 % of its annual energy demands from renewable energies, if fluctuations are neglected (EnergyMap Brandenburg, 2013). Therefore, the lignite plants define the bridging technology for this transition period towards complete renewable energy system (Moeller et al. 2014). In 2012, "The Energy Strategy 2030" was introduced as Brandenburg experienced decreasing CO_2 emissions and planned further reductions surpassing Germany's aims (MWE, 2012). The agenda aims for further increases in renewable energy generation in the state (Brandenburg: 162 % compared to 2007; Germany: 41 % compared to 2008) and decreases in CO_2 emissions (Brandenburg: 72 % compared to 2007; Germany: 55 % compared to 2008; Moeller et al. 2014), bringing Brandenburg at the forefront of the "*Energiewende"*.

The 2020 scenario consist of 8.8 GW wind energy, 4.8 GW photovoltaics, 0.4 GW of bioenergy. In order to meet a renewable energy scenario of 2030, approximately 9.5 GW wind energy, 10.2 GW photovoltaics and 0.4 GW of bioenergy will be needed (Moeller et al. 2014). Wind energy in Brandenburg already has the highest energy capacity amongst other installed renewables (NEP, 2012; LBV, 2012; Twele et al. 2012; The windpower.net 2016). Brandenburg's current wind energy capacity of 6.1 GW per capita (population 2.5 million) led to it being the apical region of the world for wind energy development (Quitter, 2010; Walker, 2010). Therefore, in both the energy strategy scenarios, wind energy in particular is increasingly explored as the main source of renewable energy, leading to the on-going and the further proliferation of wind farms in the state (LBV, 2010; EEG-Anlagenregister 2011).

With such increase in development of onshore wind energy (IWES, 2017), the pressure on birds and their habitats would obviously continue to grow simultaneously, making unproblematic locations increasingly rare (Reichenbach, 2017). With EU's strict species protection legislation affecting approvals for the construction of wind farms, coupled with a lack of thorough knowledge on the actual cumulative impacts on the species, the expansion of wind energy in Germany appears quite a tedious process. Additively, there is growing pressure to establish effective mitigation measures. Therefore, inevitable future research should be focused also should primarily focuses on combating long-term the detrimental impacts at the population-levels by delineation of effective mitigation strategies at the planning stages itself.

1.2 Study area and approach

1.2a Study area

Brandenburg

The study area for this project was restricted to the regional extent of Brandenburg, Germany. The Federal State of Brandenburg, being the fifth-largest German state is located in the north-eastern part of Germany and covering an area of approximately 29,479 km^2 (**Figure I-1**), 45 % of which is agricultural land and 37 % forests (Glemnitz et al. 2015).

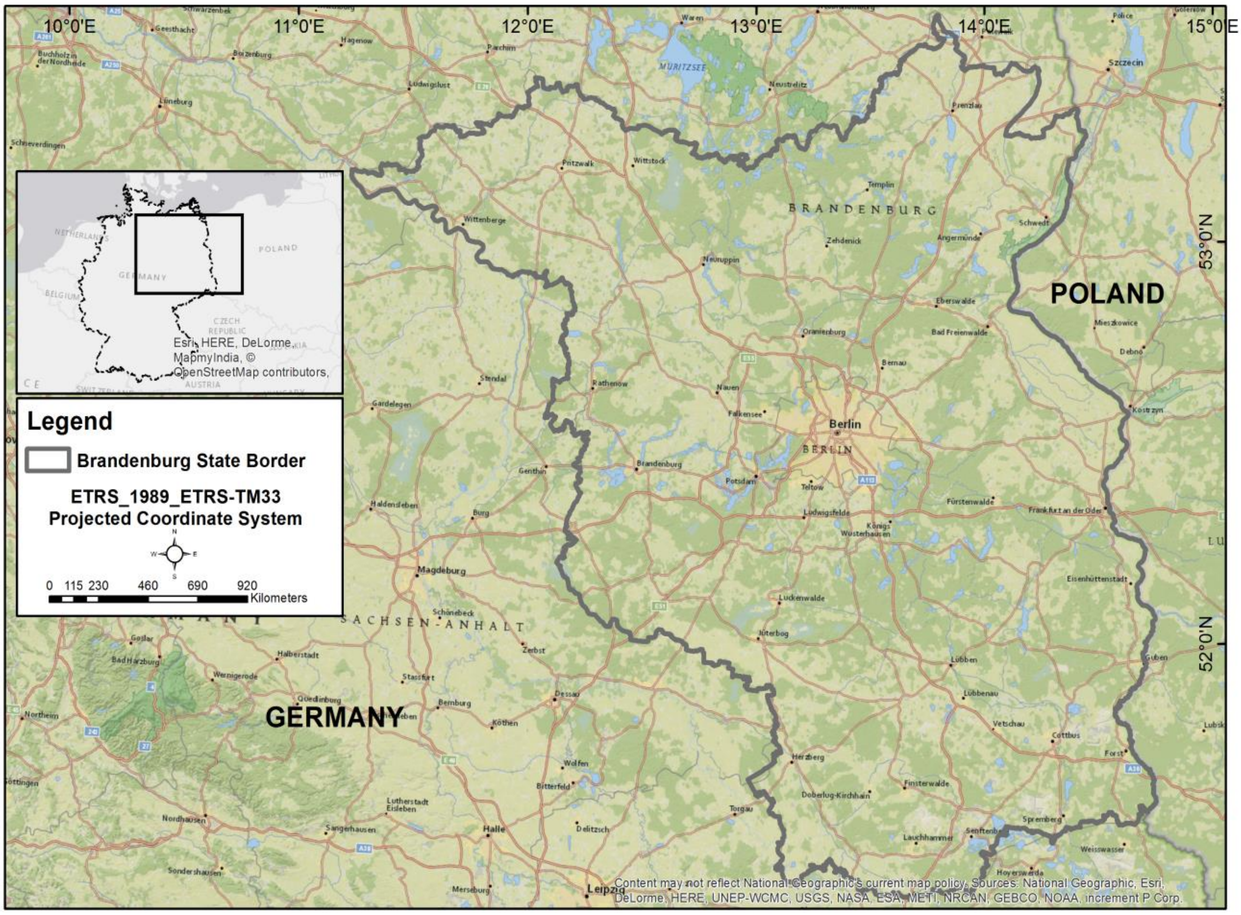

Figure I-1: The study region: Brandenburg, Germany (Data: National Geographic, ESRI, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRGAN, GEBCO, NOAA, increment P. Corp)

The landscape consists of plateaus and hills alternating with river valleys, sandy, gravelly substrates. The sandy and loamy soils are covered with coniferous forests, whereas drift and peat areas and floodplains carry more diverse vegetation. This broad range in soil fertility with the divergent distribution determines the regional agricultural land use capacities, predominantly distributed among four dominant crop species; winter rye, maize, winter wheat and winter oilseed rape, together covering 64 % of the total area utilized for agricultural purposes (Glemnitz et al. 2015). The agricultural production is limited by annual precipitation (450 to 600 mm per year).

Brandenburg, with an average elevation between 30 and 50 meters above sea level is additionally interspersed with around 27,000 km of lowland rivers and around 3,000 lakes (Kamp et al. 2004). In addition to around 50,000 smaller waterbodies, so called depressions or kettle holes, similar to the lakes were largely formed as a result of the last ice age. The Elbe, Oder, Havel, Spree, and the Schwarze Elster are the major flowing rivers in the region (MUGV 2009). For most of the rivers extreme high floods do not exist; in other cases, such floods are very rare. However, if they occur, the areas of the shallow waters flooding the lowlands along the river Oder or between the rivers Elbe and Havel can have a large extent. Additionally, the ice marginal valleys are characterized by high ground water levels year-round, with higher retention potentials and low discharge from the landscape. Backwaters levels are generally lower than 3 to 5 meters, with only a few existing dams (Kamp et al. 2004). The great wealth of waters underpins a species-rich and unique ecosystem for plants and animals.

Forests comprise around one-third of Brandenburg, with the largest contiguous forest areas being Schorfheide and Kyritz-Ruppin heath in the north, the extended forest areas between Frankfurt (Oder) and Oberspreewald in the east, as well as the Fläming in the west, along with forested regions in the Baruth Glacial Valley and Lausitz in the south (MUGV, 2009).

Another one-third of the state is taken up by 15 large reserve areas, including eleven nature parks, three biosphere reserves, and one national park. Grouped under the countrywide umbrella of the National Natural Landscapes, the administrations of these large reserves are actively involved in ecologically friendly regional development, nature tourism, and environmental education (MUGV 2009). Focal point is the integration of conservation into land use. Furthermore, the FFH Directive (Fauna Flora Habitat Directive 1992–92/43/EWG) on the Conservation of Natural Habitats and of Wild Fauna and Flora and the EU Birds Directive from 1979 has brought 620 communal use areas (FFH areas) and 27 bird sanctuaries (Special Protection Areas – SPA) in Brandenburg, incorporated into the European protection system Natura 2000 (MUGV, 2009; Glemnitz et al. 2015).

With approximately 2.6 million inhabitants the structurally weak federal state of Brandenburg has one of the lowest population densities in Germany (88 persons per km^2) (Moeller et al. 2014), Making it the world's number one location for wind power development in 2010 (Quilter, 2010).

1.2b Approach

Species distribution modelling

This study aims to further advance research on bird collisions at wind turbine structures, for the development of adequate conservation measures for bird populations; by pre-construction identification of collision risk areas in the landscape, accurately guiding wind farm installations in areas avoiding the collision risk areas and advising post-construction fatality search operations in case of extant wind turbines already installed in these collision risk areas. The study makes a relevant contribution for the identification of these priority areas by employing approaches of species distribution modelling (SDMs).

SDMs are empirical models that relate field observations to environmental predictors, based on response surfaces derived from statistical or theoretical calculations (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005; Araújo and Guisan, 2006; Elith et al. 2006; Franklin, 2010; Peterson, 2011; Santos et al. 2013; G. Arroita 2017). Predictive modelling of species distributions offers a possible solution to this challenge, by combining occurrence data with environmental variables (such as temperature, precipitation, altitude or land-use) considered to influence the presence of the species studied (Santos et al. 2013). The production of the subsequent model for the species provides insights into their habitat preferences and tolerances.

Now, as collision rates differ among wind farms, even among wind turbines within the same wind farm, the occurrence of fatalities should also be logically related to a specific range of values of the set of environmental variables associated with the location of the wind farms, more accurately with the positioning of wind turbines within them. The collision data when used paradoxically as a proxy for species presence against the environmental variables enable the prediction of risks areas of bird collisions at wind turbine structures prior to installations in future energy development scenarios via SDMs. The pro-active approach identifies environmental conditions that in combination elevate the chances of collisions, classifying wherever such combinations exists in the landscape prone to collision risks.

Therefore, utilizing this approach the main idea behind the study was to:

1. predict collision prone areas in the landscape for birds on wind farm installations

2. assess the environmental variables that promote the collision phenomenon
3. identify the range of parameters for each of these variables, sensitive to the collision risk
4. relate the collision predictions to the regional density of the target species to delineate areas of particularly higher strike susceptibility amongst the assessed areas, because of underlying substantial residing population of the species and also
5. superimpose the collision predictions with areas under the already functional and proposed phases for the construction of wind farms to check for overlaps.

Possible limitations of the approach arise when the complete range of environmental conditions that could promote bird collisions at wind turbine structures would not be incorporated (meteorological, ornithological). My focus was to particularly highlight ONLY landscape features around the locations of the WTs, especially to delineate the effect of sensitive distances of WTs to the landscape features. Other influencing factors, like, e.g. the influence of the seasons, technical turbine specifications, ornithological behaviors were ignored. I did not make any stratification regarding this.

Moreover, with continuous advancements in turbine specifications (related to rotor blade lengths, turbine tower heights etc.) to generate more and more energy, along with no possible control on meteorological conditions or ornithological behaviour that together govern bird collisions at wind turbines. The best step forward was to focus on the landscape and delineate ecologically sensitive distances to habitat elements and avoiding these distances for turbine installations.

Apart from this, in my modelling procedures- the carcass records available from the extant wind turbines do not fully represent the extent of causalities. This would lead to the development of conservative models that might fail to predict all the potential areas where the collision phenomenon might occur on turbine installation. Carcass records are already known to show strong biases, with respect to different survey methods, spatial limitations, variations in carcass persistence times and searcher efficiencies with differing species and substrata involved (Erickson et al. 2014). It is not only difficult but also sometimes impossible to account for multiple influencing factors to standardize the available data on detection of fatal collisions by the resulting carcasses detected (Korner-Nievergelt et al. 2011).

To approximate these associated detections, I used presence–only modelling approaches, neglecting the number of bird carcasses detected at each of the search operations, without extrapolating the likely number of individuals that might have died considering the detection biases involved. I utilized the spatial information of the detected carcasses to ascertain the combination of landscape-based variables influencing the collision phenomena at the spatial location of the respective turbine where the bird carcasses were detected.

Conclusively, I tried to identify potential collision risk areas in the landscape prior to wind farm installations by determining these landscapes based "ecogeographical variables" (and their range of values) that promote the collision phenomenon; to assist the impact assessment at the proposed wind farm locations. Therefore, help lower casualties by focusing monitoring efforts at the extant turbines already installed in the collision risk areas, and mitigation efforts at the proposed turbines to be installed in these areas.

The replicability of this approach allows its applicability to a further wider range of taxa, across study regions beyond the scope of this study, thus enabling the determination of collision risk areas for any other fauna as well in relation to wind farm siting.

Chapter II: Research Objectives

2.1 Objectives

The core contribution of the project is to aim for spatial allocation of wind turbines in the landscape, avoiding bird collisions. The following three central research questions were formulated. The thesis is structured according to the respective research questions formulating a manuscript each, to be published in internationally recognized, peer-reviewed journals forming the core of this thesis.

2.1a RESEARCH QUESTION I.

The worst affected group of birds at wind turbine structures? Are their respective collision niches relatable? In advent of overlaps, can the easily detectable species serve as suitable proxies for birds in general for purposes of impact assessments?

Based on the above-mentioned key questions, this work assesses the collision niche profile of the worst affected bird-groups at the wind turbine structures in the federal state of Brandenburg, Germany. The specific objectives were:

OBJECTIVES:

1. to assess the collision sensitive portion of the ecological niche for each of the worst affected bird-groups at wind turbine structures, Raptors, Pigeons and Doves, Crows, Larks for the state of Brandenburg.
2. to identify the ecogeographical variables indicating strong relation to the positioning of the collision niche of each of the groups.
3. to identify the collision niche positioning differentiations between each of the groups and assessments of the ecogeographical variables most responsible for their respective collision niche separations.
4. to assess the collision niche breadths and respective collision niche overlaps between each pair of the bird-groups.

2.1b RESEARCH QUESTION II.

Is the mitigation of bird collisions at wind turbine structures possible using the abilities of predictive modeling; a) can the possible spatial collision risk areas based on the collision probabilities be ascertained b) is it possible to further segregate the collision risk areas under different probability thresholds for c) turbines in their approved and proposed stages of development? and c) in cases of extant turbines already installed in these areas- recommending their regular inclusion in carcass search surveys.

Based on the above-mentioned key questions, this work investigates the utility of Random Forests (RF) for the predictive modelling of the impacts of wind turbine structures on bird collisions in the federal state of Brandenburg, Germany. The specific objectives were:

OBJECTIVES:

1. to evaluate the utility of Random Forests (RF) for the predictive modelling of the impacts of wind turbine structures on observed bird collisions (presence) and un-observed bird collisions (absence) against ecogeographical variables in the federal state of Brandenburg, Germany.
2. to determine the relative model strengths and the relative model accuracies of RF for each of the frequently-hit bird-groups at wind turbine structures; Raptors, Pigeons and Doves, Crows, Larks. In addition to the model accuracy statistics provided by RF, examine the model accuracy using another approach; AUC-RF.
3. assess the predictive collision risk areas based on the different probability thresholds of collision (between 0 and 1), to only detect the areas with exceptionally lower collision probability thresholds, to be interpreted as the actual “no risk areas”.
4. to determine the important rank-wise ecogeographical variables best explaining the collision (presence) response phenomenon in case of each of the bird-groups.
5. to determine the variable interaction of each of the ecogeographical variables with the collision (presence/absence) phenomena criteria.
6. to visualize each of these ecogeographical variables and examine them against both presence and absence response using the discrete data.

2.1c RESEARCH QUESTION III.

What is the strike susceptibility of birds/specific bird-group/specific bird species at wind turbine structures? By a conjunct between their assessed collision patterns and their regional densities, is it possible to investigate avenues of spatial segregation.

Based on the above-mentioned key questions, this work investigates the susceptibility and the collision patterns of specifically the Common Buzzard (*Buteo buteo*) at wind turbine structures in the federal state of Brandenburg, Germany to assess possible avenues of spatial segregation. The specific objectives were:

OBJECTIVES:

1. to determine the spatial distribution of the collision potential for buzzards at wind turbine structures using BRT models; (Boosted Regression Trees) on observed buzzard collisions (presence) and un-observed buzzard collisions (absence) against ecogeographical variables in the federal state of Brandenburg, Germany.
2. to determine the relative influence of the ecogeographical variables on the collision response (logarithmic scale of response variable) and observing the pattern of the response against each of the ecogeographical variables.
3. to determine the largest pair-wise interaction of two ecogeographical variables on the response, predicting suitability of the response in combination of solely the two ecogeographical variables in question.
4. to develop a conjunct model using the predicted collision potential in relation to the regional density of the buzzard population, to ultimately develop a strike susceptibility model for the species in the state.
5. to overlay the turbine locations under the approved and proposed categories of development in the state with the developed strike susceptibility model, to highlight the percentage of power assigned to these categories coming from zones demarcated as risky for buzzards against the turbine collision phenomenon.
6. to overlay the turbine locations under the functional category of the state to the developed strike susceptibility model, to highlight the turbines to be definitely included in fatality search operations.

2.2 Structure of the thesis

This work is structured in three main sections (Chapter III-V), each relating to one of the outlined research questions forming the core of this thesis. Chapters III – V are written as stand-alone manuscripts to be published in internationally recognized, peer-reviewed journals. They thus fulfill the formal requirements of a cumulative doctoral dissertation. Since, each chapter is structured into sections, such as background information, study area, data and methods, results, discussion, and conclusions, a certain amount of recurring material throughout the thesis is unavoidable. The three core chapters were published or prepared as follows:

Chapter III: Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2018) Collision sensitive niche profile of the worst affected bird-groups at wind turbine structures in the Federal State of Brandenburg, Germany. Scientific Reports. 8: 3777.

Chapter IV: Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2020) Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany. Conservation Science and Practice. 2(6): e199.

Chapter V: Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2019). Predicting strike susceptibility and collision patterns of the Common Buzzard (*Buteo buteo*) at wind turbine structures in the federal state of Brandenburg, Germany. PLOS ONE. 15(1): e0227698.

Chapter III: Collision sensitive niche profile of the worst affected bird-groups at wind turbine structures in the Federal State of Brandenburg, Germany

Scientific Reports (2018) 8: 3777

Anushika Bose, Tobias Dürr, Reinhard A. Klenke and Klaus Henle

The final article is available at: https://doi.org/10.1038/s41598-018-22178-z

Abstract

Biodiversity-related impacts at wind energy facilities have increasingly become a cause of conservation concern, central issue being the collision of birds. Utilizing spatial information of their carcass detections at wind turbines (WTs), we quantified the detections in relation to the metric distances of the respective turbines to different land-use types. We used ecological niche factor analysis (ENFA) to identify combinations of land-use distances with respect to the spatial allocation of WTs that led to higher proportions of collisions among the worst affected bird-groups: Buntings, Crows, Larks, Pigeons and Raptors. We also assessed their respective similarities to the collision phenomenon by checking for overlaps amongst their distance combinations. Crows and Larks showed the narrowest “collision sensitive niche”; a part of ecological niche under higher risk of collisions with turbines, followed by that of Buntings and Pigeons. Raptors had the broadest niche showing significant overlaps with the collision sensitive niches of the other groups. This can probably be attributed to their larger home range combined with their hunting affinities to open landscapes. Identification of collision sensitive niches could be a powerful tool for landscape planning; helping avoid regions with higher risks of collisions for turbine allocations and thus protecting sensitive bird populations.

Keywords: Birds, carcass monitoring, collision niche, distance effects, ecological niche factor analysis (ENFA), landscape planning, and land-use types.

Introduction

Global environmental change strongly impacts the structure of biological communities (Sala et al. 2000; Gil-Tena 2009) leading to accelerated biodiversity loss. There is an increasing concern about the negative effects of climate change on biodiversity, ecosystem services, and human society as a whole (McLeish, 2002). Concerns about the impacts of climate change on society have triggered shifts in energy systems of several countries, among them Germany, with a high investment in the renewable energy sector (McLeish 2002; Pasqualetti et al. 2004). The expansion of renewable energy is a central element of the German Federal Government's climate and energy policy. The target for 2020 is to produce 30% of the electricity from renewable energies (Meyerhoff et al. 2010). Particularly wind energy is increasingly explored as an alternative energy source, leading to the widespread construction of wind farms.

On the other hand, this growing production of wind energy is accompanied by the emergence of new conservation issues; in particular, the collision of birds and bats through direct impacts with the turbine structures (Higgins et al. 2007; Bellebaum et al. 2013). Additionally, the indirect effects of the loss of nesting and foraging habitats add on to the concerns mentioned above (De Lucas et al. 2007). Therefore, environmentalists and managers have argued against the installation of wind farms in areas with high densities of birds (Atienza et al. 2008). They make the simplistic assumption that the higher the abundance of individuals of a given species at a particular site, the higher is their susceptibility to collisions with wind energy structures installed at that particular site (Carrete et al. 2011). This assumption has been readily challenged by many researchers, since their findings show that the pre-construction bird abundances and the observed numbers of carcasses as a measure of post-construction bird collisions through detections are not closely related (De Lucas et al. 2008; Carrete et al. 2011).

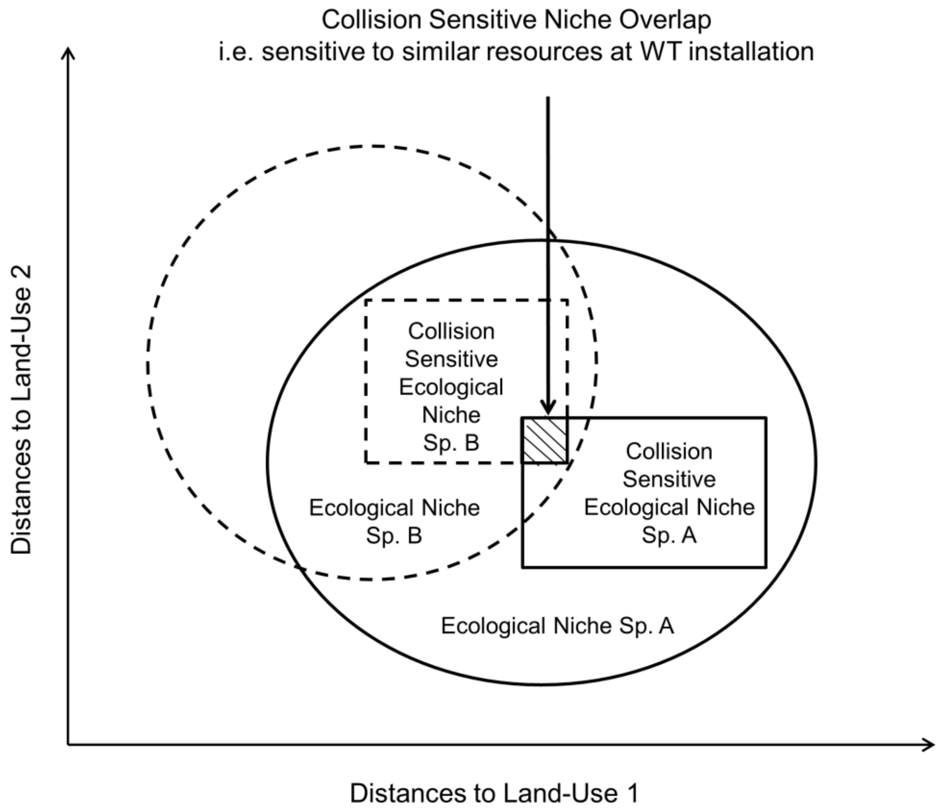

Figure III. 1: Thematic diagram explaining the collision sensitive ecological niche with respect to the ecological niche against distance to edge-based land-use classes.

In order to resolve this contradiction and to correctly guide the installation of future wind farms several researchers have tried to assess the effects of wind farms on wildlife by monitoring collisions after the construction of wind turbines (WTs) (De Lucas et al. 2008; Carrete et al. 2011; Ferrer et al. 2012). These long-term detections are based on carcass search operations conducted around the turbines. They underestimate the actual number of individuals being killed to a different degree due to a) spatial incompleteness related to non-uniformity in the searches, b) temporal incompleteness related to duration and periodicity of intervals between the searches, c) incomplete detection related to variability in carcass persistence time of birds of different sizes, and d) variation in detection probabilities related to the types of vegetation cover, substratum and the species involved in the searches (Erickson et al. 2014). These shortcomings limit the ability to compare sites and to determine the cumulative impacts of turbines on species as well (Young et al. 2003). However, there are studies that have accounted for some of these short comings by correcting for detection biases (Nievergelt et al. 2013; Bellebaum et al. 2013), or by comparing searcher efficiencies and carcass persistence times by trials using surrogate carcasses (Erickson et al. 2014). Few other studies have also highlighted the effects of landscape on the detected bird collisions, particularly of features around the locations of the WTs (Pruett et al. 2009). Our study changes the perception of this view to their spatial aspects and tries to highlight the effect of distances of WTs to habitat elements of different categories in the surrounding landscape. Distance values and thresholds to edges of habitat elements, e.g. special objects like nesting trees, are often required when policymakers ask for information ensuring safe deployment of WTs. The increase and decrease of the collision risk at distances in the immediate vicinity or away from these specific features can thereby propose safer placements of WTs in the landscape and identify areas where the risks of bird collisions could be minimized (Kiesecker et al. 2011).

In response to similar concerns regarding the direct collision-based impacts of wind farms on birds, we analyzed long-term carcass detections from monitoring operations in the state of Brandenburg, Germany, in relation to the local landscape. We evaluated the effects of distances between turbines and different land-use types on collision risks, specifically for the worst hit taxon related groups of birds in our sample, using the multivariate approach of Ecological Niche Factor Analysis (ENFA), which is based on Hutchinson's *n*-dimensional hypervolume (Hutchinson, 1957; Hirzel et al. 2006; Blonder et al. 2014). We ascertained their collision niche; a part of their fundamental ecological niche and obviously their realized ecological niche (Araujo and Peterson, 2012), only representing a part inside their respective existent hyperspace that is influenced by the deployment of technical infrastructures causing potential collisions, thus referred to as the "collision sensitive ecological niche" (Figure III. 1). We focused on assessing the similarities and dissimilarities between these collision sensitive niches of all the bird-groups under study, to enable the guidance of potential management interventions across multiple groups.

Materials & Methods

Study area

The study area, the Federal State of Brandenburg (Figure III. 2), is located in the north-eastern part of Germany. It covers an area of approximately 29,500 km^2, interspersed with around 27,000 km of rivers and around 3,000 lakes. Half of the state's area is utilized by agriculture and for livestock raising and roughly another one-third of the region is covered by forests (Kamp et al. 2004). Over the past two decades, WT structures have contributed substantially to the landscape of Brandenburg and have emerged as a new cause of bird loss (Dürr, 2009).

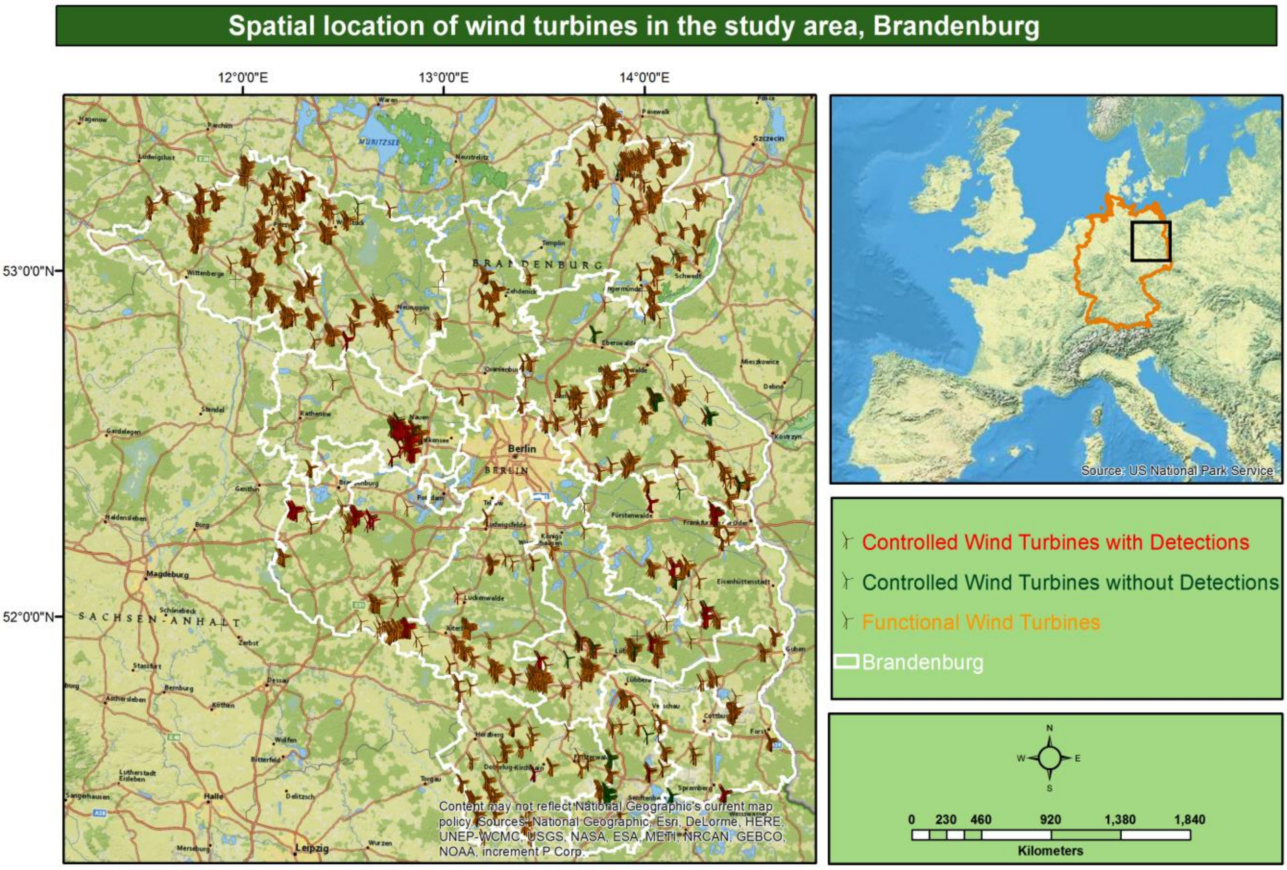

Figure III. 2: Study area showing the spatial locations of all the functional Wind Turbines surveyed (with and without carcass detections). *ESRI. ArcGIS Desktop: Release 10.1. Redlands, CA: Environmental Systems Research Institute.*

Carcass search data

Carcass detections were spatially limited and available from 69 of the 3811 wind farms currently functional in the state, comprising of 617 turbines with rotor diameters varying from 40 m to100 m and nacelle heights varying from 41.5 m to 160 m. A total of 7428 search operations were made between 2000 and 2011 with around 1–31 (mean 8.1) turbines reportedly controlled per search, out of which only 450 searches detected bird carcasses. The time interval between these search operations (searching the same turbine) varied between 1 and 188 days with a median of 2 days (mean 5.3 days); (Bellebaum et al. 2013). The data were collected either in special monitoring surveys following the construction of a wind park (carcass searching) as requested by the authority responsible for permission to construct wind parks according to the German nature conservation and planning law on federal and state levels. Further data provided to this database were based on single sampling actions e.g. either by the state agency mentioned above and only a few from collision victims accidentally found by private people during a walk or other leisure activities on their own property or on public land.

More information about the sampling can be found at:

http://www.lugv.brandenburg.de/cms/detail.php/bb1.c.312579.de

We know about the problems related to species-specific carcass persistence, searcher efficiency, and substratum or vegetation cover (Erickson et al. 2014). However, because it is not only difficult and partly also impossible to account for this and to standardize the data, we used a rather conservative approach neglecting the detailed but often very biased information. Instead, we solely utilized the respective spatial information of the detected carcasses to ascertain the combination of predictors influencing the collision phenomena at the spatial location of the particular turbines where the bird carcasses have been detected.

The general assumptions we follow in this paper are the following:

the allocation of WTs in a certain distance to habitat elements (land-use factors) and the combination of factors may have an influence on the probability to collide, other factors, that are independent of the special allocation mentioned in (a) like, e.g. the influence of the season, are ignored. We don't make any stratification regarding this, turbines, that have been controlled during the study, but had never shown any collisions, are used as a controls, the whole analyses are based on the binary information of turbine sites without any fatalities and those where one or more fatalities belonging to one or more bird-groups considered in this study were found.

We only used a subset of carcass detections for our analyses belonging to the following taxa (families): Buntings (*n*=29), Crows (*n*=30), Larks (*n*=37), Pigeons (*n*=55) and Raptors (*n*=128) (Figure III. 3). This taxonomical grouping criterion was chosen firstly because of morphological and ecological similarity and secondly with the aim to have sufficient individuals in the subsamples for statistical testing. Secondly, this taxonomic stratification followed was ultimately based on similar morphologies and ecological processes among the detected species. Such stratifications are based on linkages between taxonomic and functional diversities defined by firstly similarities in species morphologies that determine habitat and ability to colonize, followed by physiologies influencing their adaptiveness to the habitats based on rates and efficiencies of birth, death and resource utilization (Moore, 2001) influencing their collision response at the WT structures. A very few species belonging to one of the chosen groups, e.g. the Kestrel (*Falco tinnuculus*) that belongs to the order of Raptors (Accipitriformes), but shows a bigger difference with respect to ecological aspects like attraction to urban and technical structures (high buildings, chimneys) unlike other species belonging to the same order. However, in this case all 12 detected Kestrels were found near to turbines that had also fatalities of other Raptor species (Red Kite *Milvus milvus* or White-tailed Sea Eagle *Haliaaetus albicilla* or both; 5 turbines) or that were not farther away than 300 to 500 meters from those (7 turbines). Therefore, a (substantial) bias caused by these recoveries can be excluded. Besides, all other single species counts scattered over other taxonomical groups were excluded from the analyses.

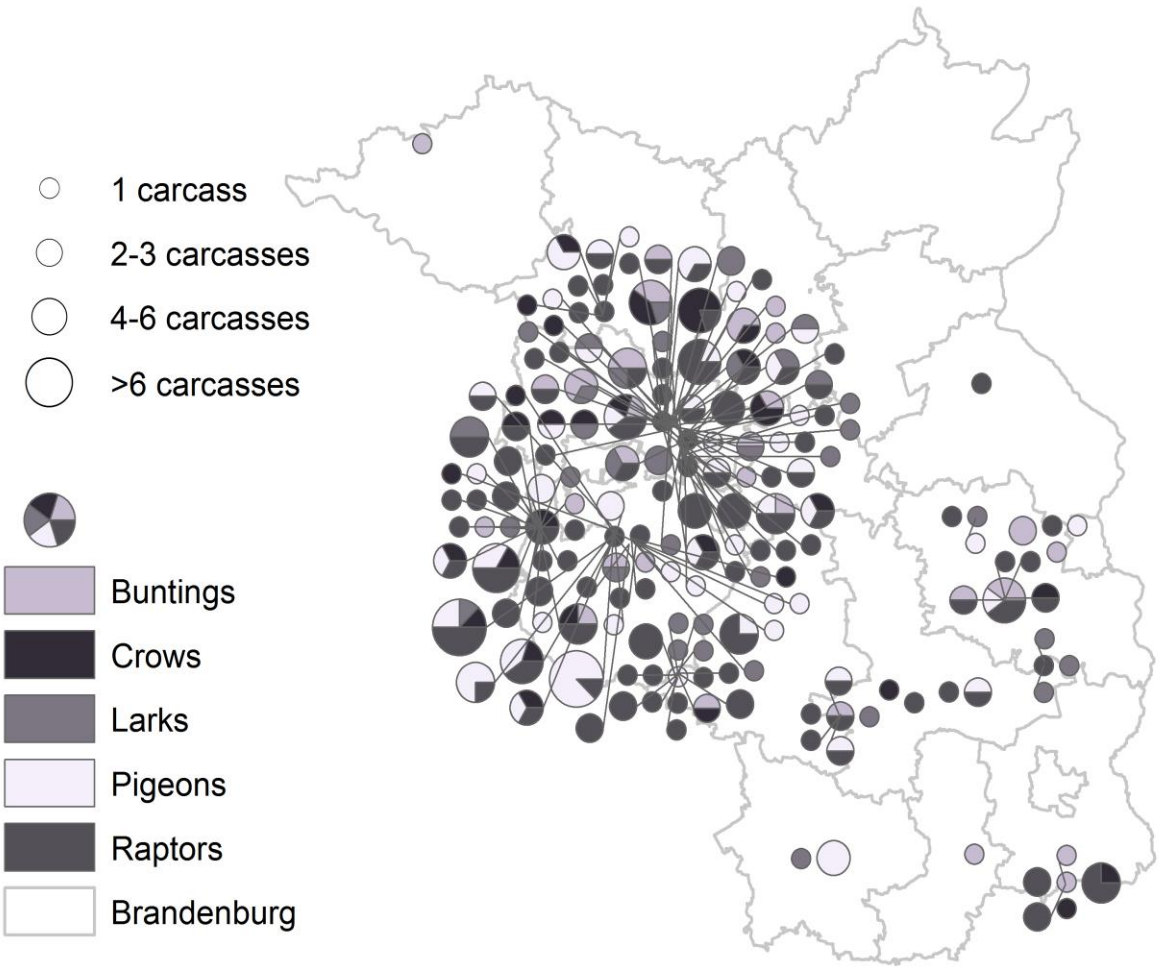

Figure III. 3: Relative abundance of the members of the worst hit bird-groups at the Wind Turbines with carcasses**.** With pies showing results of bird-group identifications expressed as relative frequencies (shading inside the pie), and total number of carcasses detected (size of the total pie) from each Wind Turbine. *ESRI. ArcGIS Desktop: Release 10.1. Redlands, CA: Environmental Systems Research Institute.*

Data preparation

Distance to edge-based land-use variables (DELV)

The detailed database of land-use provided by the Biotope Type and Land Use Mapping Project of the State of Brandenburg of 2011 (BTLNK 2011) was processed using the inclusive features at the level of the 12 major land-use classes (Table III. 1), avoiding the greater degrees of inconsistencies and lack of information associated with the succeeding subordinate classes. The different types of land-use classes were separated, features of the individual land-use classes were transformed to polylines and pre-processed individually for the creation of Euclidean distances at a cell resolution of 100 m for the whole study area using ArcGIS version 10.1 (ESRI Inc. 2012). The resolution of 100 m was chosen to find a compromise between accuracy, size of the raster maps, and available computer memory respectively processing time. Also, recommendations to policymakers are based on a resolution that is rarely higher than 100 m. For the ease of interpretation, the created Euclidean distances were prefixed with a negative or a positive sign, denoting distances inside or distances outside of the feature of a particular land-use class (Chapter VIII: Annex: Figure A1). For using these distances based land-use variables in ***Biomapper 4.0*** software http://www.unil.ch/biomapper (Hirzel et al. 2007) we converted the ArcGIS generated ESRI grids into IDRISI raster formats.

VARIABLE	DESCRIPTION	COVERAGE (%)	VARIABLE ACRONYM
Bushlands	Deciduous bushes, field bushes, tree-lined roads, tree groups and riparian woods	**0.79**	**B**
Fields	Plow lands, arable lands and other farmlands	**35.11**	**F**
Forests_forestry	Forests and commercial forests	**35.51**	**FF**
Flowing_watercourses	Streaming waters, springs, small flowing rivers and channels	**0.39**	**FW**
Green_areas_settlements	Biotopes of green areas and open spaces including parks, gardens and village greens	**1.66**	**GS**
Grass_forbs	Meadows, pastures, grasslands, lawns and forb areas	**16.37**	**GF**
Ruderal_areas	Anthropogenic raw soil sites and ruderal areas with or without very few vegetation	**0.26**	**RA**
Shrublands	Dwarf shrubs, heathlands and conifer bushes	**0.35**	**S**
Special_biotas	Special biotopes including valleys, plantations, commercial gardens and tree nurseries	**0.87**	**SB**
Settlements_structures	Buildings, roads, paths, traffic and industrial areas, railroads and village like developments	**5.73**	**SS**
Still_watercourses	Still waters, lakes, small waterbodies, reservoirs, ponds and mine waters	**2.21**	**SW**
Wetlands	Mosses, swamps, sedges and peat cutting sites	**0.73**	**W**

Table III. 1: Distance to edge-based land-use variables (DELVs) used as predictors in the Federal State of Brandenburg, Germany.

Data analysis

Ecological-niche factor analysis

With the multivariate approach of ENFA, based on Hutchison's niche theory (Hutchinson 1957, Hirzel et al. 2006) we determined the collision sensitive ecological niche (for the sake of brevity called collision niche). We used turbines (with and without collisions) as sampling points. Surveyed turbines without collisions served as controls. Sampling points are thus restricted to the existing turbines in the landscape; firstly giving insights into the structure of landscape suitable for turbine installations (under existing policies e.g. places with strong steady wind, places away from forests, places away from settlements etc.). Amongst these sampling points some points have collisions, giving insight not only regarding the structures of the landscape that are suitable for turbine installations under current policies, but additionally to those factors more likely leading to collisions. Our study uses the spatial information of the turbines with detected bird carcasses, where presence (Hirzel and Lay, 2008) in a grid cell is given the value of 1, and absence in a grid cell (no turbine or no turbine with detected carcasses) is given the value 0. This Boolean response map covering the whole study area acts like a mask that is analyzed in ***Biomapper 4.0*** software for ENFA against the gridded maps of the predictor variables to elucidate the combination of distances to different land-use types that lead to an increased risk of collision with WTs.

We specifically evaluated these combinations of distances for the worst hit taxon related groups of birds in our sample (Buntings, Crows, Larks, Pigeons and Raptors), focusing on similarities and dissimilarities between these bird-groups.

To enable the guidance of potential management interventions, we used ENFA based on Hutchinson's *n*-dimensional hypervolume (Hutchinson 1957) in a little different way. ENFA normally condenses the overall information into two indices; the first index is 'marginality' of the focal species, defined as the ecological distance between the species optimum and the mean habitat within the reference area (Hirzel et al. 2002). In our special case, it maximizes the multivariate distance between the predictor variables for the cells with detected collisions and the predictor variables for all cells without turbines or collisions within the reference area. This index provides information about the extent to which the species collision sensitive niche differs with respect to the combinations of distances to different land-use types from that of the most frequent set of combinations available in the entire spatial multivariate reference set of the study area (Ayala et al. 2009) (Figure III. 2). In our study, global marginality values closer to 1 will signify that there is a substantial difference with respect to the combination of distances between the composition and configuration of the study area as compared to the composition and configuration of the collision sensitive niche. Contrarily, a value closer to 0 will imply no difference (Hirzel et al. 2002).

The second and the following indices are the 'specialization' indices. They maximize the specialization of a focal species, defined as the ratio of the ecological variance in mean habitat to that observed for the focal species (Hirzel et al. 2002). The values account for the decreasing specialization in subsequent order and denotes the extent of the species distribution width with respect to the overall distribution of conditions in the reference area (Ayala et al. 2009). The inverse of specialization is a measure of the species tolerance (Hirzel and Lay, 2008) to conditions that are increasingly distinctive from their optimum. In our study, species with greater specializations will have lower tolerance and their collision sensitivity at WTs will substantially increase only when its placement meets special combinations of distances based on spatial relations between different land-use types that promote collisions.

Niche differentiation and overlap

We firstly used linear discriminant analysis (LDA) to discriminate among turbines with the detections of birds belonging to the different taxon related bird-groups and the turbines with no detected bird carcasses, independent of the niche concept. LDA was conducted using the MASS package (Venables et al. 2002) in R (R Development Core Team, 2013).

Secondly, we used the discriminant factors from the ENFA following the niche concept to make discriminant analyses using ***Biomapper 4.0*** software, between (pairs of) the bird-groups and compare the distribution of predictor variables amongst the groups simultaneously. This procedure then computes a factor maximizing the difference between the groups while minimizing the intra-group variance (Jung and Czetwertynski, 2013). The resulting discriminant factors are therefore basically linear combinations of the predictor variables, with their coefficients identifying every variable’s contribution to discriminate the collision sensitive niche between each pair of the bird-groups under consideration. Hence, the discriminant scores highlight the variables for which the pair of groups in question differ the most.

Thirdly, the scores of their respective discriminant factors from the ENFA analyses were also used to compute indices quantifying their respective collision niche breadths and to assess their similarities on the basis of pairwise niche overlap analyses. The discriminant factor from one of the group is used and interpreted in the form of signs indicating the direction towards the first or the second species in comparison. The Hurlbert index (*B')* was used to measure the niche breadths (Hurlbert, 1978), where B' ranges from 0 (corresponding to specialized niche) to 1 (corresponding to generalized niche) (Sattler et al. 2007). Lloyd's asymmetric overlap index *(Z*) was computed to assess the extent of niche overlaps between the groups, where larger *Z* values and a smaller associated reciprocal *Z* value for a given pair of species signify greater niche overlap (Hurlbert, 1978) by the former on the latter. And lastly, the first discriminant factor from each of the respective ENFA of the bird-groups were also used to visually represent the respective predictor variables-based conditions favoring collisions in the landscape of Brandenburg.

Distribution distances and comparison between turbines where fatalities were registered and those where no fatalities were found so far

We have investigated the group-wise significant differences between the distribution of the WTs with fatalities and the WTs without fatalities against different DELVs using the Kolmogorov-Smirnov test (Massey, 2012), using the maximum vertical deviation between their respective cumulative distributions as the statistic ***D*** and their respective ***P***-values reporting the significance of difference. The hypothesis regarding the difference in their distributional form is rejected if ***D*** is greater than the critical value based on a table for the chosen significance level or if the directly calculated ***P***-value is smaller than the chosen significance level.

Although it has advantages of being non-parametric and making no assumptions about the distribution of the data (Massey, 2012), there are practical issues as well when applying the Kolmogorov-Smirnov test to fatality search data, primarily due to low detectability, either due to being rapidly scavenged or due to being moderately vulnerable to the collision phenomena. Not taking into account such effects can lead to artificial results of small numbers that ultimately leads to wrong conclusions about the result of the Kolmogorov-Smirnov test, which we do consider in the discussion of the results.

Data availability**:** All data files created in this study are available from the Dryad Digital Repository: DOI***:*** http://dx.doi.org/10.5061/dryad.j1h2v.

Results

Ecological-niche factor analysis

Corresponding to the set of value combinations based on the land-use distance variables, the global marginality values for Crows (*M*=1.17), Larks (*M*=1.18), Buntings (*M*=0.98), Raptors (*M*=0.98) and Pigeons (*M*=0.99) (Table III. 2). All bird-groups showed a similar degree of specializations [Buntings (*S*=2.40), Crows (*S*=2.54), Larks (*S*=2.43), Pigeons (*S*=2.29)], except for Raptors with a substantial lower value of specialization (*S*=1.82) (Table III. 2). As global tolerance is the reverse of specialization, the collision tolerance at WTs for Buntings and Larks will be lower as compared to that of Raptors. Table III. 3 shows the relative influences of each predictor variable on the marginality and specialization factors for the five bird-groups at WTs (See Chapter VIII: Annex: Table A1 for the associated coefficient values of these factors), representing the influence of the respective predictor variables on the collision sensitivity that increases the risk for the birds to collide with a WT.

Raptors:
The raptor marginality factor only accounted for 13% of the total sum of eigenvalues of the factors. The coefficients of arable lands loaded substantially to both axes, marginality and especially specialization (F1 = -0.41 and F2 = -0.79; Chapter VIII: Annex: Table A1) indicating strong evidence for the discovery of Raptor carcasses at distances closer to or even inside of fields and other arable lands. Their marginality coefficients also showed correlations to distances away from forests and forestry areas (0.50), green and open spaces outside human settlements (0.40) and grassland and forb areas (0.33), with the loadings for distances farther from forests being higher than the distances inside the fields. Likewise, their first specialization factor provided further insights on their collision niche breadth, being spanned mainly between distances farther from shrub-lands and distances inside the fields, with the weight more on the latter. In this factor, the variance in the sample of points, described by the turbines where fatalities of Raptors were found, is 1/16 the variance found in the sample of all other points in the study area. The coefficients showing the relation to the distances from fields and arable lands suggest that the distances to the edges of this particular land-use type has a major impact in limiting collision risk for Raptors.

BIRD GROUPS	MARGINALITY *(M)*	SPECIALIZATION *(S)*
Buntings	0.98	2.54
Crows	1.17	2.40
Larks	1.18	2.43
Pigeons	0.99	2.29
Raptors	0.98	1.82

Table III. 2: Collision marginality (M) and specialization (S) values for the worst hit bird-groups at wind turbines in the Federal State of Brandenburg, Germany**.** Marginality represents the extent of how different the group's collision habitat is from the mean conditions available in the study area; an increasing M indicates increasing marginality. Specialization S represents the breadth of the collision prone niche for each group, with S >1 indicating some degree of specialization.

Crows and Larks:

The specialization factor for Crows accounted for 33% and that of the Larks accounted for 38% of the total sum of eigenvalues of factors, both illustrating high levels of specializations towards distances to flowing watercourses and arable lands, respectively. The niche is not very marginal (1.14, 1.10) for Crows and Larks, respectively, and in the same range as the one of the Raptors. However, the variance in the sample of turbines with fatalities for Crows and Larks is 1/12 and 1/6.5 of the variance found for all other points in this landscape. Their marginality coefficients showed similar preferences to all predictor variables, i.e. discovery of their carcasses showed correlations with the distance closer to fields and arable lands (-0.37 and -0.40, respectively) and with the distance away from forests and forestry areas (0.47 and 0.58, respectively) and grassland and forb areas (0.41 and 0.43, respectively) as well. In their first specialization factor, the variance in their sample of turbines is substantially smaller than the rest of the study area, with a ratio of 1:31.64 and 1:29.45, respectively.

Buntings:

Buntings marginality and specialization factor accounted for 15% and 34% of the total sum of eigenvalues of factors, respectively, also indicating strong relationship with distances closer to fields and other arable lands (Fields coefficient F1 = -0.44 and F2 = -0.64; Chapter VIII: Annex: Table A1). In contrast to other bird-groups, the marginality factor of Buntings indicated that their carcass detections were more strongly influenced by distances away from forests and forestry areas (0.64) than by distances away from grasslands and forb areas (0.34) and green and open areas around human settlements and bush-lands (0.26).

Pigeons:

The marginality factor of Pigeons accounted for only 22% of the total sum of eigenvalues of factors, with marginality coefficients indicating that Pigeon detections increased with the distances from forests and commercial forests (0.47), green and open spaces outside human settlements (0.36), and grassland and forb areas (0.38). The marginality and specialization axes (available = 11.348 and 21.641, respectively) indicated strong relationships with distances to fields and other arable lands (Fields coefficient F1 = -0.45 and F2 = -0.36; Chapter VIII: Annex: Table A1).

The ratio of specialization accounted for by the first specialization factor for every bird-group suggests that the effects on their niche breadth were largely influenced by their respective factor coefficients, but the marginality factor (the ratio of the variance at all sample points versus the variance of the samples at turbines with carcasses) for Raptors accounted for less specialization (4.86:1) than for the Larks (6.57:1), Buntings (8.91:1), Pigeons (11.35:1) or Crows (11.79:1), indicating that they displayed a more restrictive range than Raptors for those conditions for which they differed from the mean of the study area (Figure III. 4).

Niche differentiation and overlap

The Linear Discriminant Analysis (LDA) provided weak discrimination among the location of WTs without detected carcasses and those with detected carcasses of the five worst hit bird-groups (Figure III. 5). The first two linear discriminant axes (LD1 and LD2) together explained 25–48% of among-group variance in the LDA (Chapter VIII: Annex: Table A3). LD1 was positively influenced by distances to still watercourses and negatively influenced by distances to forests and forestry areas. LD2 on the other hand was strongly influenced by distances to flowing watercourses.

Hulbert's niche breadth index indicated that the turbines where Raptors had collided showed a more general and greater expanse along landscape distance variables compared to that of the other groups (Table III. 4). This is also consistent with the results of the LDA (Figure III. 5).

Lloyd's asymmetrical niche overlap index consistently showed significantly greater overlap of the common collision space by the turbines with Raptor detections, followed by that of the Pigeon detections, especially on the detections of other bird-groups that have insignificant reciprocal overlaps on the former groups. The lowest overlap index was observed for the overlap of turbines with Bunting detections (Table III. 5).

Discriminant Analysis

Supporting the results of niche differentiation and overlaps, the pairwise discriminant analyses between simultaneous pairs of each of the bird-groups also highlighted very low separation of their collision space. The predictor variables that still highly influenced the fundamental separations between the collision spaces of most of the group pairs are provided in (Chapter VIII: Annex: Table A2. Positive values (≥0.2) indicate variables that primarily contribute to the collision sensitive niche of the first bird-group of the pair, negative values (≤ -0.2) to that of the second bird-group of the pair (Chapter VIII: Annex: Figure A2).

Table III. 3: Contribution of the 12 predictor variables to the marginality and specialization factors of the ENFA, of the worst hit bird-groups at wind turbines in the Federal State of Brandenburg, Germany. Marginality factor 1 – +: the focal bird-groups were detected at locations with values higher than the average cell value for the particular predictor variable, i.e. avoidance; -: an increasing negative distance may be understood as preferring proximity for the particular predictor variable. Specialization factor 2 – *: the focal bird-groups occupied a narrower range of values for the particular predictor variable than those available in the reference set. The greater the number of symbols (+,-,*) the narrower the range; with each symbol reflecting an influence of 0.10 on a scale between 0 and 1 (+ = 0.1, ++++++++++ = 1), where 0 indicates a very weak correlation/low expression of the respective factor.

	MARGINALITY					SPECIALIZATION				
	Buntings	**Crows**	**Larks**	**Pigeons**	**Raptors**	**Buntings**	**Crows**	**Larks**	**Pigeons**	**Raptors**
Eigenvalues	1.15	1.14	1.10	1.21	1.13	0.33	0.33	0.38	0.29	0.34
Specialization accounted for by the factor	Factor 1 (15%)	Factor 1 (14%)	Factor 1 (11%)	Factor 1 (22%)	Factor 1 (13%)	Factor 2 (34%)	Factor 2 (33%)	Factor 2 (38%)	Factor 2 (30%)	Factor 2 (34%)
Bushlands	++	+++	+++	++	++	*	**	**	*	*
Fields	----[1]	----[1]	----[1]	----[1]	----[1]	******	***	********	****	********
Forests_forestry	++++++	+++++	++++++	+++++	+++++	**	0	*	**	***
Flowing_watercourses	+	0	+	0	+	*****	*******	****	***	****
Green_areas_settlements	+++	++++	+++	++++	++++	0	0	*	***	**
Grass_forbs	+++	++++	++++	++++	+++	*	*	*	**	*
Ruderal_areas	++	++	++	++++	++	***	*	*	***	*
Shrublands	++	+	++	+	+	**	****	*	**	**
Special_biotas	0	+	-[1]	-[1]	0	**	*	***	***	0
Settlements_structures	+	++	+	+++	++	**	**	*	***	*
Still_watercourses	+	++	+	++	++	**	*	**	*****	*
Wetlands	+++	+++	++	+	+++	*	**	*	**	*

Differences in Distance Distributions

The comparison of distributions of distances found for turbines where fatalities were registered with those where no fatalities were found so far gave additional insights regarding the importance of the different land-use classes for the bird-groups under investigation are shown in Table III. 6 and Figure III. A3. For the Raptors the distributions shifted significantly between distributions of turbines with carcasses as compared to turbines without carcasses, mainly for five land-use classes (flowing watercourses p=0.000 (towards shorter distances), still watercourses p=0.045 (towards farther distances), green areas around settlements p=0.000 (towards farther distances), shrublands p=0.045 (towards farther distances), and settlement and structures p= 0.030) (towards farther distances)), while for Pigeons they were found for three land-use classes (flowing water courses p = 0.000 (towards shorter distances), grassland and forb areas p = 0.038 (towards farther distances), ruderal areas p=0.003 (towards farther distances)). Only two albeit different land-use classes were significantly different for Larks (grassland and forb areas p=0.013(towards farther distances), Shrublands p= 0.004 (towards farther distances)), Crows (flowing watercourses p=0.004 (towards shorter distances), green areas around settlements p=0.006 (towards farther distances)) and Buntings (forests and forestry areas p=0.016 (towards farther distances), special biotas p=0.002 (towards farther distances)) respectively. The differences exist not only in median values but also in the extent and partly skewness of the distributions as can be seen from Chapter VIII: Annex: Figure A3.

Discussions

The guidelines of the EU Habitats and Bird Directives make provisions to ensure the protection of wildlife against WT structures and recommend wind projects to be preceded by impact assessment studies and succeeded with post-construction (baseline) collision monitoring programs to determine impacts on wildlife at the project sites (EU Guidance on wind energy development in accordance with the EU nature legislation, 2011). We used long-term collision detections from wind farms in the state of Brandenburg for the assessment of the worst hit groups of birds at WTs – Buntings, Crows, Larks, Pigeons, and Raptors. The main intent behind our examination was to assess to which particular land-use types and at what distances to these land-use types do WTs promote or reduce the collision risk. Distances are often required when policymakers ask for information ensuring safe deployment of WTs. Therefore, the results can be helpful in showing the increase and decrease of the collision risk at distances in the immediate vicinity or distant away from specific land-use types, thereby facilitating proposing safer placements of WTs in the landscape. Therefore, we analyzed the carcass detections in relation to the local landscape, specifically against the distances between and within multiple land-use types to the WT sites, to ascertain special combinations of distances leading to a higher risk of bird collisions.

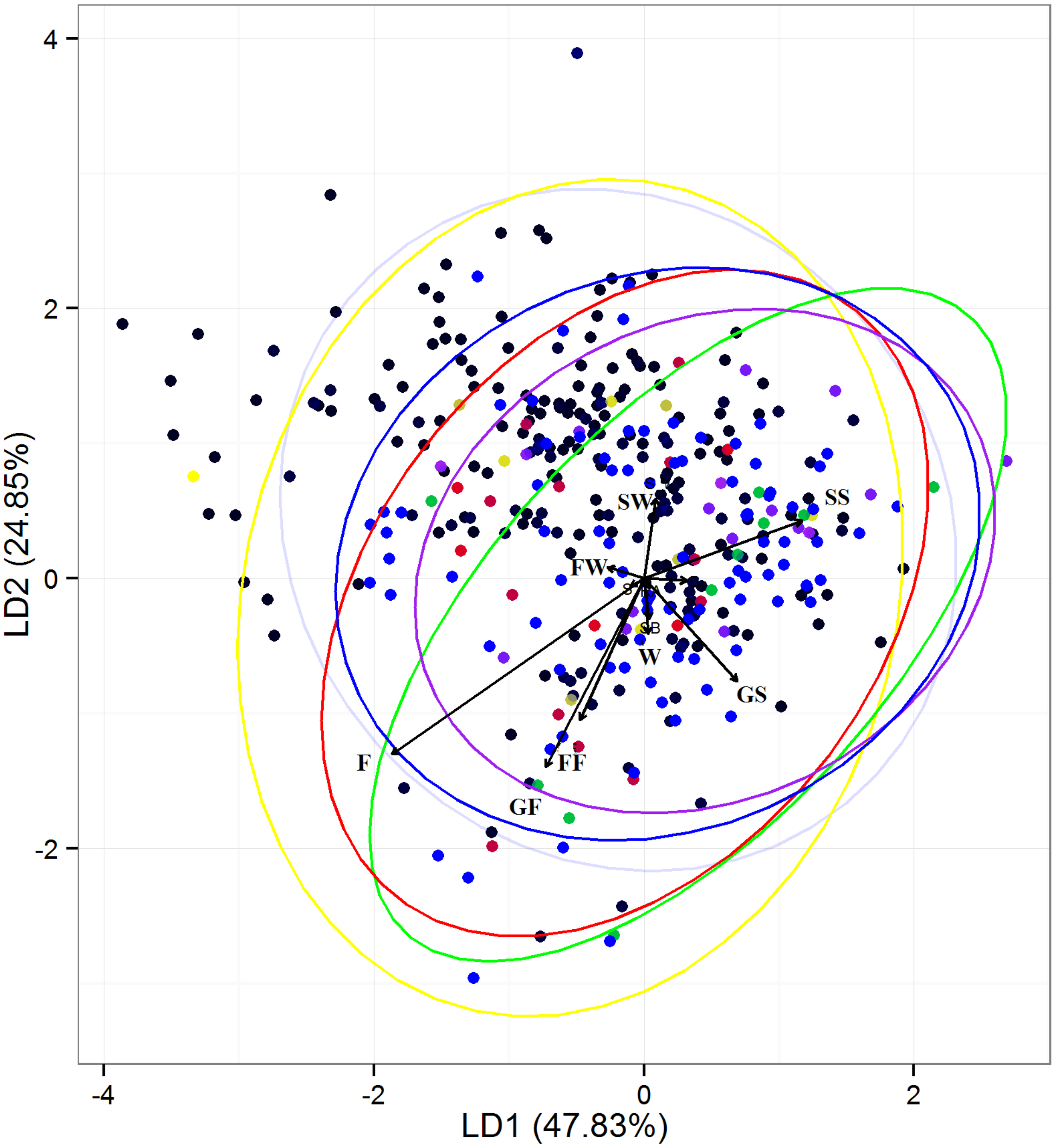

Figure III. 4: Collision sensitive niche positioning based on marginality coefficients (eigenvectors) ascertained by ENFA of the worst hit bird-groups at wind turbine structures in the study area. The colors yellow, green, red, purple and blue denote Buntings, Crows, Larks, Pigeons and Raptors, respectively. [1]*Acronyms corresponding to the predictor variables are described in Table III. 1.*

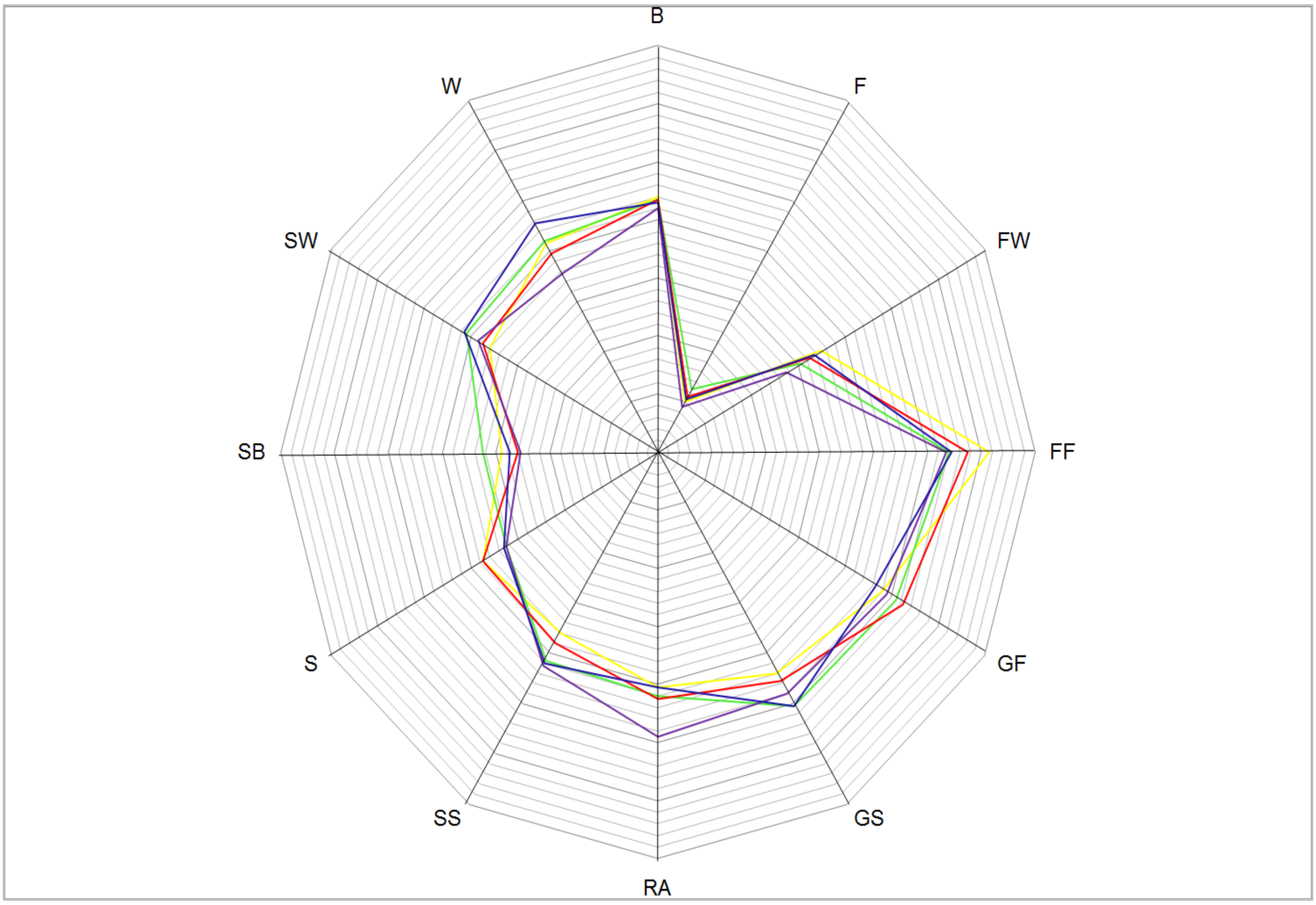

Figure III. 5: Linear discriminant analysis of the predictor variables representing the collision - no collision space showing the placement of the worst hit bird-groups at wind turbine structures in the study area. Black denotes no detections of collisions; yellow, green, red, purple and blue denote the bird-groups of Buntings, Crows, Larks, Pigeons and Raptors, respectively. [1]*Acronyms corresponding to the predictor variables are described in Table III. 1. (Please refer to Chapter VIII: Annex: Table A3 for the other variables and information regarding their respective influence on the axes)*

BIRD-GROUP	HULBERT'S NICHE BREADTH *B'*
Raptors	0.41
Pigeons	0.36
Larks	0.32
Buntings	0.30
Crows	0.26

Table III. 4: Hulbert's niche breadth index (B′) for the worst hit bird-groups at wind turbines in the Federal State of Brandenburg, Germany. *B' may range from 0-1, with 0 and 1 corresponding to specialists and generalists, respectively.*

NICHE OVERLAP	Raptors[1]	Pigeons	Crows	Larks	Buntings
Raptors	-	9.34	5.74	7.38	4.71
Pigeons	18.48	-	5.87	7.57	4.93
Crows	17.80	9.20	-	7.86	4.06
Larks	19.62	10.17	6.74	-	5.02
Buntings	16.84	8.92	5.38	7.67	-

Table III. 5: Lloyd's asymmetrical overlap indices (Z) for the collision sensitive niches of the worst hit bird-group at the wind turbines in the Federal State of Brandenburg, Germany, and their reciprocals. [1]*The small Z values, and larger associated reciprocals for each of the bird-groups with that of the group of Raptors, signifying greater niche overlap by the latter group. Rest combinations have almost similar overlaps on each-other i.e. equivalent.*

The marginality coefficients for each group depict strong relationships between the turbines where carcasses have been detected and the following key land-use types: fields and other arable lands, forests and forestry areas, green and open areas outside human settlements and grassland and forb areas. With increasing or decreasing absolute values, signifying proximity with respect to the sign (inside -, outside +; announcing the direction). It is noteworthy that the proximity of the detections (group-wise) to particular land-use types on which our collision sensitive niche analyses (group-wise) are based, are alike.

The marginality factor of the data from Raptors further suggested higher importance of distances between turbines and green, open areas in and around human settlements as well as distances of turbines to forests. These findings are reflected in their observed carcass detections at turbines closer but outside the borders of forests and forestry areas up to distances of 2000 m (Chapter VIII: Annex: Figure A3) and is in line with expectations based on Raptor proximities to forests and forestry areas that provide them with suitable nesting and breeding places (Newton 1979; Carter et al. 2009). Our results are also in accordance with the minimum distances of wind turbines to breeding sites of Raptors as recommended by the Working Group of German State Bird Conservancies, based on species-specific telemetry studies, collision data, functional-spatial analyses, long-term observations and expert assessments, taking into account the risk of collision, avoidance and barrier effects caused by wind turbines (LAG VSW, 2014).

Raptors are also highly abundant in the fringe zones of infrastructures (Benítez-López et al. 2010), primarily due to adequate hunting options (Dean and Milton 2003), especially of many human-commensal small mammals (Millsap and Bear 2000; Mannan and Boal 2000; Ranazzi et al. 2000) and the availability of roadkill carrions (Lambertucci et al. 2009), with observed carcasses at turbines situated from their borders between 400-2400 m distances (Chapter VIII: Annex: Figure A3). They are also observed using features of the urban landscape, such as trees adjacent to open covers, fences and buildings, as shelter from wind, pollution, domestic predators, and concealment in ambush attacks on their prey and for purposes of perching, utilizing new and artificial nesting substrates (Chace and Walsh, 2006; Rutz, 2006; Roth et al. 2008; Hogg and Nilon, 2015). Pigeons likewise, another abundant bird species in built-up environments, have also adapted their nesting requirements and foraging habits to be conducive with the urban lifestyles (Harris et al. 2016) and particularly, green and open areas and urban parks surrounding heavily urbanized areas, settlements and infrastructures have higher densities of these species, as they take advantage of food discarded by humans favoring a more stable presence (Leveau and Leveau, 2016), explaining the increase in Pigeon carcass detections at turbines closer to their borders, with detection primarily observed between 1000 m and up to 1700 m (Chapter VIII: Annex: Figure A3).

The marginality and specialization factorial axes of all the bird-groups also indicate strong relationships with distances to arable lands, highlighting their impact in limiting their collision sensitive niches. In case of Raptors, their associations with certain elements of the agricultural landscapes, especially arable lands and open fields, is primarily because of hunting facilitated by mowing or use of low-stature crops (Baker and Brooks, 1981), exposing preys to aerial predators (Fitzpatrick, 1996). Moreover, the fallow land at the mast foot provide suitable small-mammal habitat in the agricultural landscape, irrespective of low- or high-stature crops (Dürr and Langgemach, 2006). Placement of WTs generally has to follow many criteria; the site under consideration should have a strong potential for wind and should neither be near to settlements nor to areas of important habitats for birds or protected species that could be harmed (LAG VSW, 2014). With the reluctance of local people to install WTs near their homes, project developers often attempt to install wind energy facilities on agricultural land, particularly on arable land dominated by open fields (Millon et al. 2015). These areas are also characterized by large plots of grassland or large fields of crops. Therefore, we can find almost all of the already constructed WTs inside of fields or open grasslands. This spatial preference also adds on to the ecological affinities certain bird-groups, particularly Larks show towards open landscapes. They avoid tall, dense vegetation cover (Donald et al. 2001), and nest and forage in open agricultural fields, that influences most of their habitat preferences and reproductive success (Eraud and Boutin, 2002; Morris et al. 2004), which in turn increases their risk of colliding with the turbine structures closer to the borders of fields, grasslands and open areas. With carcasses detected near to wind turbines situated between -400 m up to 100 m distances from the borders of fields and majorly detected between 300 m and 700 m distances from the borders of grasslands and open areas (Chapter VIII: Annex: Figure A3).

ENFA results also show that Raptors have the lowest global specialization value in comparison to the other bird-groups and also a comparatively larger niche breadth as per Hulbert's niche breadth analysis. The ENFA analyses and the LDA analyses also denote that the coverage of the collision space by Raptors is larger compared to that of the other bird-groups, explaining their asymmetrical niche overlap with the other bird groups. Raptors have a greater home range (Rodríguez-Estrella et al. 1998; Tanferna et al. 2013) as compared to many other birds of smaller size, and venture across distances to utilize perch and prey availability (Chace and Walsh, 2006). This indicates that the greater Raptor overlap is either an effect of the comparably larger parameter space covered by the Raptors or a better coverage of the detections in the study area because of their larger sample size, i.e. the exceptionally high number of Raptor carcasses detected at WTs in comparison to other smaller birds. This is primarily due to higher searcher efficiencies in combination with longer carcass persistence times for Raptors (Erickson et al. 2014).

The least observed niche overlaps based on turbine sites where collisions were detected show that the rather restrictive collision niche of Buntings has an insignificant overlap with the collision niches of other bird-groups, especially Crows. Crows being generalist omnivores (Marzluff and Neatherlin, 2006) and Buntings being shrub-land specialists (Rudnicky and Hunter, 1993; Rodewald and Vitz 2005, mostly show niche differentiations on grounds of their specific preferences towards proximity to green and open areas in and around settlements and proximity to shrub-lands respectively. This is in accordance with our pairwise discriminant analysis, showing turbines with Bunting and Crow detections having fundamental niche separations related to the distances to the edges of shrub-lands (favoring Bunting detections) and green areas around human settlements (favoring Crow detections). These results are also consistent with ENFA, where Buntings show higher global specialization values as compared to other groups.

Overlaps of the respective collision niches of the bird-groups indicate similar sensitivities of birds to the multiple land-use combinations, whereas niche differentiations indicate the reverse. Niche overlap is often used to indicate potential for competition between species (Costantini, 2009; Sattler et al. 2013; Jung and Czetwertynski 2013).

However, in this study, with respect to renewable energy infrastructure the overlaps between species provides insights into their similar or disparate sensitivities to distances from different land-use types that allow directing safer turbine positioning for protecting multiple bird-groups at once as well as for targeting specific groups with limited overlaps with other groups.

		B[1]	F[1]	FF[1]	FW[1]	GAS[1]	GF[1]	RA[1]	S[1]	SB[1]	SS[1]	SW[1]	W[1]
Buntings	*D*	0.094	0.143	0.297	0.201	0.123	0.099	0.173	0.297	0.359	0.215	0.158	0.153
	P	0.970	0.629	0.016*	0.218	0.805	0.952	0.385	0.016	0.002**	0.158	0.501	0.548
Crows	*D*	0.144	0.190	0.206	0.334	0.322	0.190	0.304	0.201	0.291	0.156	0.153	0.167
	P	0.601	0.259	0.180	0.004**	0.006**	0.258	0.011	0.204	0.017	0.496	0.526	0.411
Larks	*D*	0.150	0.157	0.226	0.000	0.128	0.270	0.249	0.299	0.148	0.077	0.138	0.112
	P	0.425	0.369	0.060	1.000	0.625	0.013*	0.028	0.004**	0.437	0.987	0.528	0.782
Pigeons	*D*	0.102	0.157	0.112	0.393	0.097	0.201	0.257	0.158	0.164	0.158	0.147	0.158
	P	0.691	0.177	0.575	0.000***	0.748	0.038*	0.003**	0.175	0.143	0.172	0.239	0.174
Raptors	*D*	0.053	0.075	0.059	0.294	0.238	0.079	0.098	0.141	0.136	0.149	0.142	0.113
	P	0.952	0.662	0.894	0.000***	0.000***	0.589	0.321	0.045*	0.061	0.030*	0.045*	0.181

Table III. 6: Results of the comparison of distance distributions with the Kolmogorov-Smirnov test found for turbines without and turbines with fatalities for the worst hit bird-groups with regards to the predictor variables. *Significance levels * <= 0.05, ** <= 0.01, *** <= 0.001.* [1]*Acronyms corresponding to the predictor variables are described in Table III. 1.*

Conclusion

Using the simplistic ordination procedure of ENFA, based on presence-absence of WT hit bird carcasses; we found that individuals of the worst hit group of birds in the state of Brandenburg showed an appreciable extent of overlaps between their collision spaces. Raptors showed the greatest overlaps with all other groups, most likely due to their broad range, covering the parameter space of the reference area as well as their appreciably greater probability to be hit by the turbine structures and be detected afterwards owing to their bigger body sizes that have greater persistence times and are easier to detect. Moreover, despite of the fact that our study was only based on carcass detections, it gave a detailed descriptive analysis of the turbines with collisions with respect to their placement distances to land use types. Although our method is not suitable for predictions of the impacts on and viability of bird populations, the detected greater Raptor niche overlaps compared to the other groups indicate that Raptors may serve as a suitable proxy for birds in general for purposes of impact assessments and be a safer starting point to develop and test theories in an experimental framework to better understand the relationship between landscape compositions and the risks to birds from technical infrastructures for wind energy production. Such studies will not only pave the way for future research but also enable improved guidance for management interventions and the spatial allocation of wind farms to serve the transition to renewable energies while keeping impacts on species minimal.

Chapter IV: Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany

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Abstract

The risk of collision with wind turbines remains a critical issue for bird conservation. Undoubtedly, for the continued development of wind farms to increase the energy capacity, wind farm locations must be carefully chosen going forward. This can be achieved not only by avoiding areas with higher bird densities but also by avoiding installations at sensitive distances from their ecologically important land-use types. Through analyses of the Euclidean distances to the different land-use types, we utilized the random forest (RF) machine learning algorithm to model the distance-based impacts of wind turbine locations on detected bird collisions for the frequently-hit groups of birds at WTs. Although, the predicted areas with potential collision risk in total had a small but highly dispersed expanse of approximately 2,130 km^2 across the vast 29,479 km^2 area of the federal state. Our results further segregated these assessed areas based on their different probabilities of collision thresholds (between 0 and 1) to only detect the areas with collision probabilities <0.05, which were interpreted as the actual “no risk areas”. These “no risk areas” summed to a total of merely 754 km^2 of the land space in Brandenburg, suggesting that any further planned additions of wind energy farms in the state i.e. the proposed wind turbines, to be suitably positioned only in these safer areas. Additionally, the study also enabled the identification of any existing wind turbines already installed in the remaining less safe 28,725 km^2 area of the state. These areas are also essential to be include in the collision detection surveys and bird population dynamic studies. This would further our understanding regarding the deleterious consequences of collisions at the population levels of birds, eventually helping in the formulation of adequate mitigation measures.

***Keywords*:** Wind energy structures, Bird collisions, Land-use types, Euclidean distance, Random forest (RF)

Introduction

The negative effects caused by climate change phenomena along with the depleting traditional “conventional” sources of energy have promoted high investments in the alternate sources of “renewable” energies (Kaldellis and Zafirakis, 2011), making e.g. wind power as one of the increasingly explored alternative sources of energy. Along with the development of wind power, avian collisions at wind power facilities have also developed as a rather escalating source of unnatural mortality among not only birds but also bats and other flying animals, such as insects (Corten and Feldcamp, 2001). As the number of these power structures rapidly grows across the globe, and will keep growing according to the power trends on a world-wide scale (Valença and Bernard 2015; Wang and Wang 2015), concerns have been raised in relation to the collision risks posed by wind turbines, especially for birds and bats (Voigt et al. 2015). Collisions may not only have substantial demographic consequences for many of the implicated bird taxa, in some instances, they might constitute a significant source of unnatural mortality for already severely threatened species (De Lucas et al. 2012; Eichhorn et al. 2012; Ferrer et al. 2012; Schaub 2012, Bellebaum et al. 2013; Schuster et al. 2015), putting their populations under additional and increasingly unsustainable pressure (Jenkins et al. 2010) and creating the risk of local or even global extinction.

Currently, there are more than 25,000 onshore wind turbines installed in Germany (May et al. 2017). The federal states further aim to provide up to 1.5 % of their land areas for onshore wind energy development, resulting in more than doubling their currently installed capacities. As a result, the pressure on birds will continually grow, and less problematic locations for installations will become increasingly rare. This would make it challenging to propose new wind farm locations (May et al. 2017). Therefore, the additional installation of turbines to increase the wind-generated energy capacity will require precise predictions of bird collision probabilities to allow better positioning of wind farms to avoid or at least substantially reduce the risk for such collisions.

The most simplistic solution is to avoid areas with higher bird densities, making the general assumption of a link between higher abundance and higher rates of mortality at wind turbine structures (Atienza et al. 2008; Carrete et al. 2011). But this assumption has already been challenged by many researchers monitoring post-installation bird collisions at wind power facilities. They found contradictions between the pre-installation bird abundance and the detected bird mortality from collision with wind turbines once operations commenced (De Lucas et al. 2008; Carrete et al. 2011; Ferrer et al. 2012). These mortality detections were based on carcass search operations conducted around the turbines.

Generally, carcass search operation based studies underestimate or overestimate the actual number of individuals being killed; likely due to a) non-uniformity in the searches (spatial incompleteness), b) duration and periodicity of the intervals between the searches (temporal incompleteness), c) variability in the carcass persistence time of birds of different sizes (detection incompleteness), and d) variation in the detection probabilities related to the types of vegetation cover, substratum and the species involved in the searches (detection incompleteness) (Erickson et al. 2014). These shortcomings together limit the ability to compare sites and to determine the cumulative impacts of turbines on species by the identification of areas where the risks of bird collisions could be higher. Thereby, limiting the identification of safer turbine placement options in the landscape (Bose et al. 2018).

However, many studies have accounted for some of these shortcomings by correcting for carcass detection biases (Bellebaum et al. 2013; Nievergelt et al. 2013), by comparing searcher efficiencies and carcass persistence times by trials using surrogate carcasses (Erickson et al. 2014). Other studies have addressed the need to resolve these contradictions to correctly guide the installation of future wind turbines with the techniques of species distribution modelling (SDM) (Santos et al. 2013; Bose et al. 2018). SDMs generally describe the relationship between the occurrence of species and a set of predictor variables that quantify the habitat and other limiting variables (Magness et al. 2008). In this sense, SDMs are integral tools for obtaining distributions and probabilities of occurrence information (Guisan and Zimmermann, 2000) by combining occurrence data with environmental variables, such as temperatures, precipitation, altitude or land cover (Santos et al. 2013). SDMs can provide insights into the environmental sensitivities and habitat preferences of species (Anderson et al. 2003).

As collisions differ among wind farms (Smallwood and Thelander 2004; de Lucas 2008; Hull and Muir 2013), the occurrence of collisions can also be thought to be related to the specific ecological conditions that are associated with the location of the wind farm and to that of the specific habitat requirements of the species that collide (Santos et al. 2013). Therefore, collision data when used as a proxy for species presence against the environmental conditions in SDMs, enables the prediction of bird collision risk areas at wind turbine structures prior to installations for future energy development scenarios.

Our study also aimed to contribute to the identification of collision risk areas by employing the power of SDMs to carcass search detection data. Our pro-active approach identified the environmental conditions that combine to elevate the chances of collisions, by classifying the locations of these combinations occurring wherever in the landscape.

Some previous studies have also analysed the impacts of turbines on birds using the same module; but, with respect to 1) wind park based technical parameters of individual turbines (tower height, rotor radius, rotor swept area, colour, light), 2) some with that of habitat parameters; the positions of the turbines in the wind park (land use, distance of woodlands or water bodies to the mast foot of the turbine). These modules finally evaluated the accuracy of collision predictions of birds by assessing the success of future detections at the predicted locations (Grünkorn et al. 2009; Dürr, 2011, Eichhorn et al. 2012; Illner, 2012; Bellebaum et al. 2013; Hötker et al. 2013; Rasran and Dürr, 2013; Rasran and Thomsen, 2013; Schreiber, 2014; Langgemach and Dürr, 2015; Weitekamp et al. 2015; Grünkorn et al. 2016).

Our focus on the contrary, was to particularly highlight ONLY landscape features around the locations of the WTs, especially the effect of sensitive distances of WTs to the landscape features. Other influencing factors, like, e.g. the influence of the season, technical turbine specifications are ignored. We don't make any stratification regarding this. Our strict choice to focus on distance values and thresholds to edges of landscape elements, was because distances are often required when policymakers ask for information ensuring safe deployment of WTs. The increase and decrease of collision risk at distances in the immediate vicinity or distant away from these specific landscape features can thereby propose probably safer placements of WTs in the landscape and identify areas where the risks of bird collisions could be minimized in advance. Moreover, with continuous advancements in turbine specifications (related to rotor blade lengths, turbine tower heights etc.) to generate more and more energy, along with no possible control on meteorological conditions or ornithological behaviour that together govern bird collisions at wind turbines.

The best step forward would be to focus on delineating ecologically sensitive distances for taxa towards habitat elements and avoiding these distances for turbine installations (TIs).

To uncover these mechanisms, we used random forest (RF) algorithms analysing the turbines with carcass detections in relation to the local landscape, specifically against the distances between and within multiple land-use types to the specific WTs. This ascertained special combinations of distances leading to a higher risk of bird collisions, to ultimately develop collision distribution models. As RF models also allow extrapolation of the potential collision risk areas without any current TIs- they guide the avoidance of these sensitive areas for future wind farm installations. We specifically made these evaluations for the frequently-hit bird taxa in our sample (buntings, crows, larks, pigeons and raptors). With respect to collisions at wind turbines, raptors already have been the subject of maximum attention, because these birds generally have low reproductive rate, and any minor increase in mortality can have considerable consequences on their populations (De Lucas et al. 2012; Eichhorn et al. 2012; Ferrer et al. 2012; Schaub 2012; Bellebaum et al. 2013). Four of the raptor species most often reported as fatalities in Germany are, namely the common buzzard (*Buteo buteo*), red kite (*Milvus milvus*), sea eagle (*Haliaeetus albicilla*) and the kestrel (*Falco tinnunculus*), in the descending order (Dürr, 2010). Although, the large birds being reported unproportionally often, due to their larger body sizes with greater carcass persistence times. The smaller birds largely go undetected, due to their smaller body sizes and shorter carcass persistence times (Erickson et al. 2014). Therefore, our study chose to focus on all the frequently-hit taxa from the same benchmark of conservation concern.

Materials & Methods

Study area

The study area, was the federal state of Brandenburg, located in the northeastern part of Germany (Figure IV. 1). It covers an area of approximately 29,500 km^2, which has approximately 27,000 km of rivers and approximately 3,000 lakes. Half of the area of the state is used for agriculture and livestock production, and roughly another one-third of the region is covered by forests (Kamp et al. 2004). Over the past two decades, wind turbine structures have contributed substantially to the disturbance of the landscape structure in Brandenburg, Rapidly proliferating, in terms of the associated technical infrastructure installations across the entire landscape (Dürr, 2014; Bose et al. 2018).

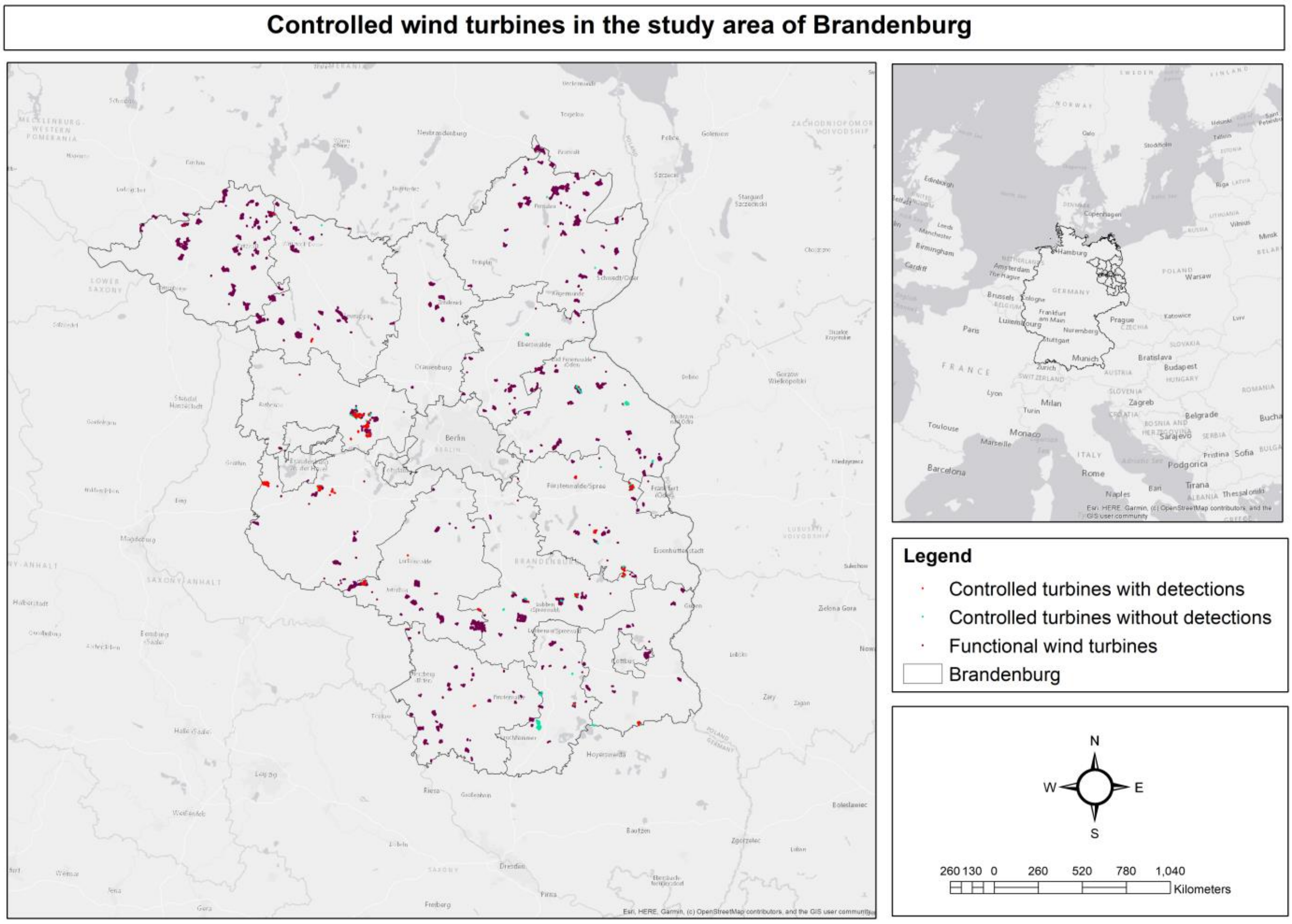

Figure IV. 1: Study area showing the spatial locations of all the functional wind turbines (surveyed with carcass detections and without carcass detections) *(from Bose et al. 2018)*.

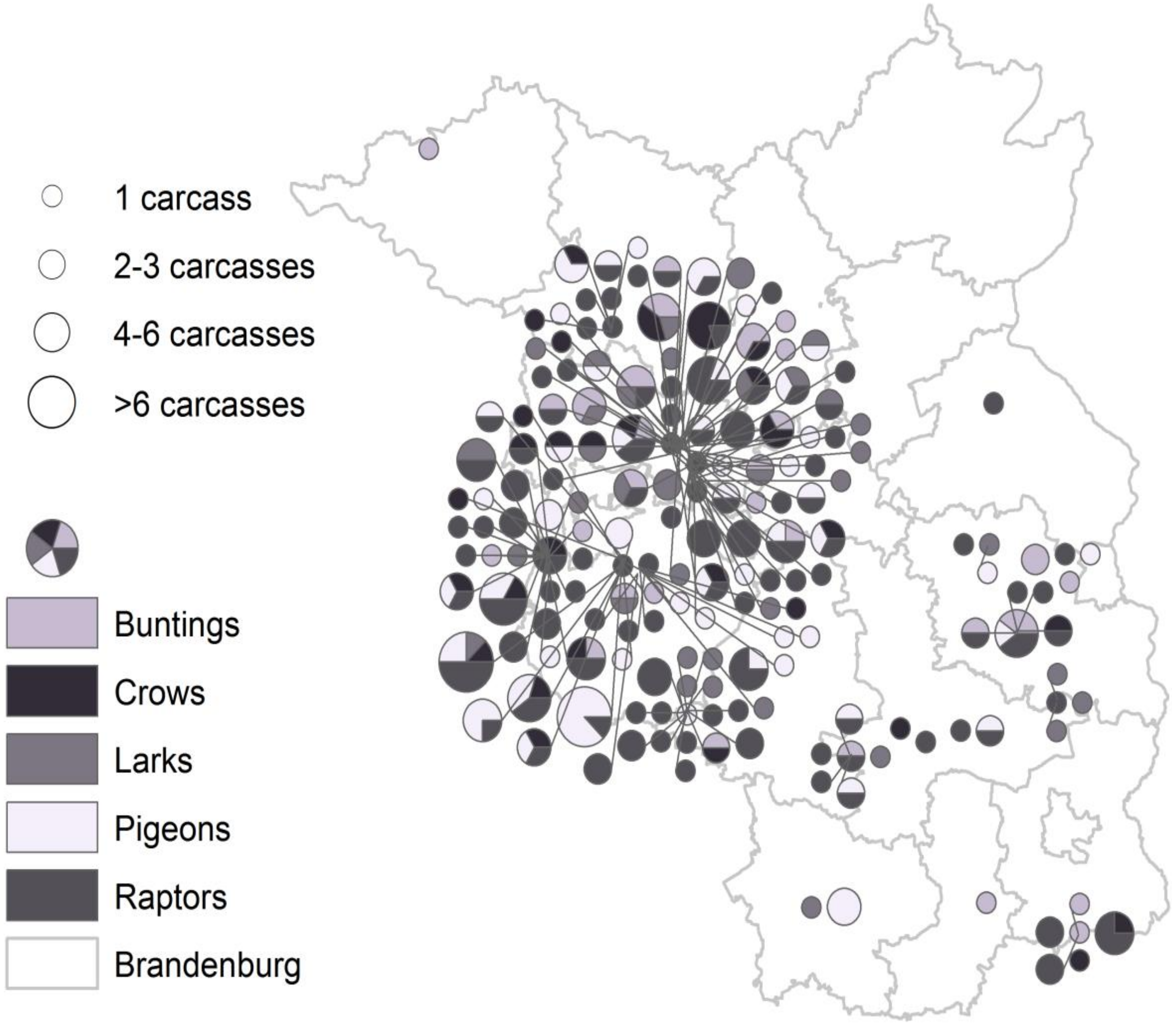

Figure IV. 2A: **Relative abundance of the members of the frequently-hit bird-groups within the carcasses detected at wind turbines in the study area,** with pies showing results of bird-group identifications expressed as relative frequencies (shading inside the pie), and total number of carcasses detected (size of the pie) from each wind turbine *(from Bose et al. 2018)*.

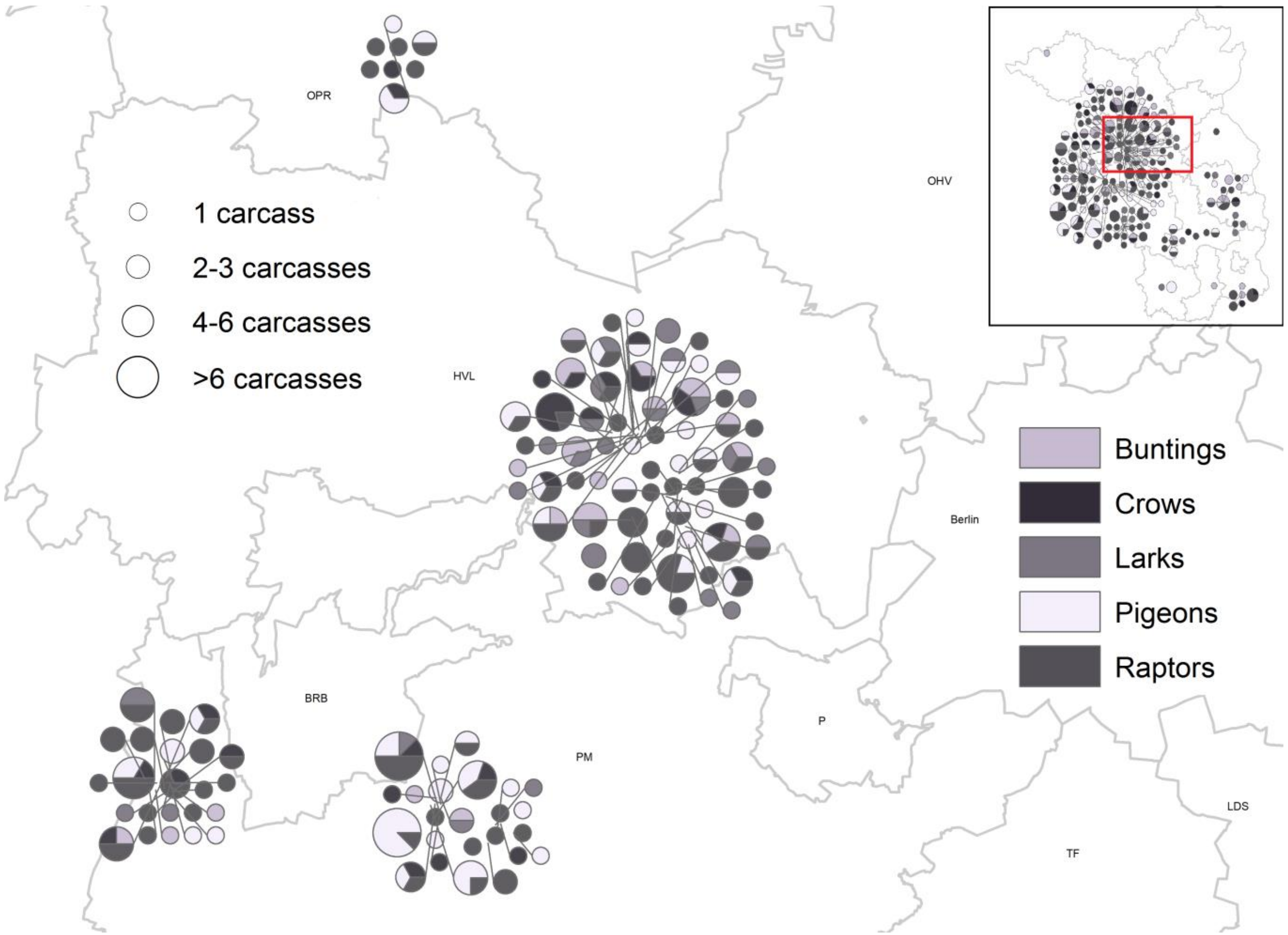

Figure IV. 2B: **Relative abundance of the members of the frequently-hit bird-groups within the carcasses detected at wind turbines in a sector of the study area.** With pies showing results of bird-group identifications expressed as relative frequencies (shading inside the pie), and total number of carcasses detected (size of the pie) from each wind turbine.

Carcass search data

This study is based on a database registering counts and locations of birds found dead as a consequence of collision with WTs in the Federal State of Brandenburg; provided by the Brandenburg State Agency for Environment. *Accessible at:*

http://www.lugv.brandenburg.de/cms/media.php/lbm1.a.3310.de/meldebogen_anflugopfer.xls

The data was collected in special monitoring surveys following the construction of wind parks (i.e., carcass search operations) as requested by the Ministry of Environment, Health and Consumer Protection for the state of Brandenburg. In general, the data provided to this database were mostly based on single sampling actions, e.g., either by the state agency mentioned above or from accidental findings of collision victims by private citizens during walks or other leisure activities on their own property or on public land. No living animal was caught or killed for this study. All animals collected and registered in this database were killed by collision with WTs independent of the sampling process and before the sampling was performed. No species were killed or manipulated for this study, they were either found dead or seriously injured after their collision, registered and provided to the authority responsible for their registration and, if still possible, overhanded to an appropriate animal welfare center for health treatment and appropriate release. There was either no permission necessary for the registration and collection of these carcasses on public land or the collection was performed in accordance with a requested monitoring or a special permission on owned land. All permissions followed the respective legislation at the federal and state levels. No illegal information is stored in this database. The database is hosted by the State Agency, which is deputized in this study by one of the authors (Tobias Dürr). More information about the sampling can be retrieved from: http://www.lugv.brandenburg.de/cms/detail.php/bb1.c.312579.de

The detections were spatially limited and available from 69 of the 3811 currently functional wind farms (mean of 5 functional turbines per windfarm, excluding the dismantled windfarms and wind turbines). The turbines were primarily concentrated towards the western and southern districts of the federal state (Figure IV. 2). 617 turbines in total were controlled: with rotor diameters varying from 40 m to 100 m and nacelle heights varying from 41.5 m to 160 m, with a power generation capacity between 1 MW to 6 MW. A total of 7,428 carcass search operations were conducted between 2000 and 2011, with approximately 1–31 (mean 8.1) turbines controlled per search operation, out of which only 450 searches detected bird carcasses in total. The time interval between these search operations (searching the same turbine) varied between 1 and 188 days, with a median of 2 days (mean 5.3 days) (Bellebaum et al. 2013; Bose et al. 2018).

Although, we are aware of the spatiotemporal inconsistencies related to species-carcass detected studies, it is not only difficult but also sometimes impossible to account for multiple influencing factors to standardize the available data on detection of fatal collisions and the resulting carcasses detected. For example, not all the birds injured by the strong turbulences or direct collisions (causing muscle ruptures, wing luxation, or bone fractures) die and fall in the immediate vicinity of the turbine they collide with. An unknown proportion will still pass this situation and fly larger distances, with suffering from severe/minimal injuries and die later because of starvation, predation or other reasons directly related to the collision event. This way, it is impossible to estimate the proportion of birds actually hit, because each of these events would have to be detected, the type and the severity of the injury has to be registered, and the fate of the still alive, i.e. escaped bird to be monitored. Although, this would only result in the information about the probability to die or the probability to survive for those birds that have experienced a collision but left the area. The second group of victims are those, that can be found in the near vicinity of the turbines post the collision event. This is the proportion of birds that suffered serious injuries due to the collision or turbulence and either lost their ability to fly or died immediately. However, even from this group only a smaller proportion can be found because of inconsistencies related to species-specific carcass persistence times, searcher efficiencies, and substratum or vegetation cover present (Erickson et al. 2014). Some of them; will simply be overlooked, unnoticed in dense vegetation, thrown out of the often-limited search range (collision caused acceleration or strong winds) and lastly eaten or carried off from the search area by predators (Bernardino et al. 2012). These recovery probabilities are related to the distance from the turbine, size and shape of the search area, size and species of the victim (e.g. big and colorful vs. small and grey or green in grey-green winter vegetation), weather (wind, rain, snow, heat), time lag between collision and control, alertness, attention and sight of the observer, and whether only humans or humans together with detection dogs are performing the survey. Use of detection dogs can increase the probability to find a carcass substantially (Paula et al. 2011; Grimm-Seyfarth et al. 2019). Ignoring these factors can cause serious bias in estimates of collision probabilities. However, the conceptual model behind the proposed factor estimates are still absent or incomplete, resulting in a constrained estimation method in the sense that the available procedures are not applicable under general circumstances either (Korner-Nievergelt et al. 2011). Enhancing this problem with very often or not, is the no information about the boundary conditions of the detected carcass dataset. Especially in our case, where the underlying material is an opportunistic set of data collected from systematic surveys of different intensity and duration, as well as accidentally found and reported carcasses. Therefore, we used a conservative approach of the detection and non-detection to assess the combination of predictors that created an increased risk of bird collisions on TIs. We solely utilized the respective spatial information of the turbines with detected carcasses and without detected carcasses, neglecting the detailed but often very biased associated information regarding: the estimated numbers of birds discovered in each detection, differences in carcass search monitoring efforts; ranging from only once controlled to many frequently and regularly controlled turbines across the all the windfarms under study (Bose et al. 2018). Additionally, we also rule out that the carcass search operations data is biased towards wind turbines, because the all the dead bird carcasses were reported to the regional authorities and not just wind turbine collision fatalities.

For our study, we used a subset of carcass detections from the following taxa only: buntings (n=29), crows (n=30), larks (n=37), pigeons (n=55) and raptors (n=128). We also analyzed the surveys where the following taxa were absent: buntings (n=491), crows (n=490), larks (n=483), pigeons (n=465) and raptors (n=392) (Figure IV. 2A; Bose et al. 2018, Figure IV. 2B). This taxonomical stratification criteria were chosen because of shared similar morphology and ecology within each category; the goal was to have sufficient individuals in each of the subsamples for statistical testing. Such stratifications are based on linkages, primarily between the taxonomic and functional diversities defined by the similarities in the species morphologies that determine their habitat preferences and abilities to colonize different areas (Moore, 2001), which also influences their similar likelihood of colliding with WT structures (Bose et al. 2018).

VARIABLE	DESCRIPTION	COVERAGE (%)	VARIABLE ACRONYM
Bushlands	Deciduous bushes, field bushes, tree-lined roads, tree groups and riparian woods	**0.79**	**B**
Fields	Plow lands, arable lands and other farmlands	**35.11**	**F**
Forests_forestry	Forests and commercial forests	**35.51**	**FF**
Flowing_watercourses	Streaming waters, springs, small flowing rivers and channels	**0.39**	**FW**
Green_areas_settlements	Biotopes of green areas and open spaces including parks, gardens and village greens	**1.66**	**GS**
Grass_forbs	Meadows, pastures, grasslands, lawns and forb areas	**16.37**	**GF**
Ruderal_areas	Anthropogenic raw soil sites and ruderal areas with or without very few vegetation	**0.26**	**RA**
Shrublands	Dwarf shrubs, heathlands and conifer bushes	**0.35**	**S**
Special_biotas	Special biotopes including valleys, plantations, commercial gardens and tree nurseries	**0.87**	**SB**
Settlements_structures	Buildings, roads, paths, traffic and industrial areas, railroads and village like developments	**5.73**	**SS**
Still_watercourses	Still waters, lakes, small waterbodies, reservoirs, ponds and mine waters	**2.21**	**SW**
Wetlands	Mosses, swamps, sedges and peat cutting sites	**0.73**	**W**

Table IV. 1: Distance to edge-based land-use variables (DELVs) used as predictors in the federal state of Brandenburg, Germany (from Bose et al. 2018)

Data preparation

Distance to edge-based land-use variables (DELV)

The detailed land-use database provided by the Biotope Type and Land Use Mapping Project of the state of Brandenburg from 2011 (BTLNK, 2011) was processed to create predictor variables for the 12 major land-use classes, this avoided greater degrees of inconsistencies and lack of information associated with their respective subordinate classes. The different types of land-use classes were separated and the features of each of the individual land-use classes were transformed into polylines and pre-processed individually to measure the Euclidean distances at a 100 m grid cell resolution for the whole study area with ArcGIS version 10.1 (ESRI, 2012). The resolution of 100 m was chosen to compromise between the accuracy and size of the raster maps and the available hardware processing time, in addition to being suitable for providing recommendations to policymakers for TI purposes. The Euclidean distances were prefixed with a negative or a positive sign; denoting distances inside the feature of the particular land-use class or distances outside the feature of the particular land-use class respectively (Bose et al. 2018) (Table 1; Chapter VIII: Annex: Figure A1).

Data Analysis

To develop models that allow the prediction of the potential collision risks areas, we used random forest (RF) algorithms (Breiman 2001; Evans et al. 2011) to quantify the relationship between carcass detection and the land-use types. We analysed the presence/pseudo-absence data of the detected carcasses for every bird group against the 12 DELVs. We used individual turbines (presence: with carcasses; pseudo-absence: without carcasses) as the sampling points, i.e., the sampling points were restricted to the surveyed and already existing turbines in the landscape. The detection of at least one carcass at one wind turbine within a grid cell was given the value of 1, and grid cells where no carcasses were detected at a turbine were given values of 0. The relationship of the responses to the 12 DELVs were determined through classification and regression; partial dependence plots were constructed with the randomForest package in R (Liaw and Wiener, 2001; R Development Core Team, 2013) with the default reported number of trees in the forest (500) and with 3 DELVs sampled at each split. The influence of the DELVs were further exemplified by the RF classifier along with examination of the response across the DELVs with conditional density plots. Apart from the RF model, we also applied another R package, AUCRF (Calle et al. 2011; R Development Core Team 2013; Calle and Urrea, 2014), as a supplementary test of the accuracy of the RF calibrations in our study. The model performance was evaluated with the cross-validation of a random dataset using 70 % of the sampled points for training and 30 % to test the model.

Results

The results from the RF models for each of the frequently-hit groups of birds at the WTs (for the classification, between 0 and 1) provided comparative model fits with good overall out-of-bag (OOB) error rates. The OOB error for the raptor collision model was approximately 9 %, with the classification error unequally balanced between the presence and pseudo-absence classes due to the imbalances in the input response data. For model evaluation, back-prediction to the k-fold cross-validated dataset demonstrated a perfect fit with an AUC of 1, and that using the AUC-RF approach was also 0.92 with an 8 % error rate. The models for pigeons, larks, crows and buntings followed this trend, exhibiting approximately 8 %, 6 %, 6 % and 4 OOB errors, respectively (with higher error rates again for the presence class in comparison to negligible error rates for the pseudo-absence class due the imbalance in the input response data). The back-prediction for these groups to the k-fold cross-validated data also provided an AUC of 1, but with the AUC-RF approach; the provided AUC values of 0.83, 0.65, 0.82 and 0.82, respectively, along with error rates of 17 %, 35 %, 8 % and 8% (Table IV. 2) respectively.

Bird-Group	OOB error rate (%)	Presence Class Error	Presence Classified Incorrectly (FP)	Presence Classified Correctly (TP)	Pseudo-absence Class Error	Pseudo-absence Classified Correctly (TN)	Pseudo-absence Classified Incorrectly (FN)	n presence	Kopt¶	OOB-AUCopt	AUC CV
Buntings	4.43	0.79	23	6	<0.001	490	0	29	7	0.82	1
Crows	5.73	0.96	29	1	<0.001	476	0	30	9	0.82	1
Larks	6.3	0.86	32	5	<0.001	471	0	37	3	0.65	1
Pigeons	7.92	0.7	39	16	0.002	449	1	55	9	0.83	1
Raptors	8.61	0.37	48	80	0.008	472	4	128	9	0.92	1

Table IV. 2: RF and AUCRF output for the frequently-hit bird-group at WTs in the federal state of Brandenburg, Germany. ¶ *Number of selected variables*

To reiterate, for the back-predictions - owing to the imbalances in the responses, the resulting model fits for all groups were deceptive; as they exhibited very small overall OOB errors, along with small cross-classification errors for the pseudo-absence class and extremely high cross-classification errors for the presence class. In conjunction with these analyses, the RF models further simulated the group-wise potential areas with or without any collisions (i.e. binary response of 1 or 0, respectively) and with the different probabilities of collision (between 0 and 1). The areas with collisions on TIs (binary response =1) in total had an overall expanse of approximately 2,130 km^2 across the 29,479 km^2 area of the federal state (Figure IV. 3; Table IV. 3). Raptors, pigeons, larks, crows and buntings contributing approximately 35 %, 48 %, 6 %, 2 % and 9 %, respectively, to the total of the assessed collision risk areas (Table IV. 3).

Bird-group	Collision risk area (*in* km^2)	Collision risk area (%)
Raptors	747.04	35.07
Pigeons	1,036.82	48.67
Larks	125.32	5.88
Crows	36.31	1.70
Buntings	184.41	8.65

Table IV. 3: Expanse of the predicted collision risk areas (*in* km^2) for each of the frequently-hit bird-groups at WTs in the federal state of Brandenburg

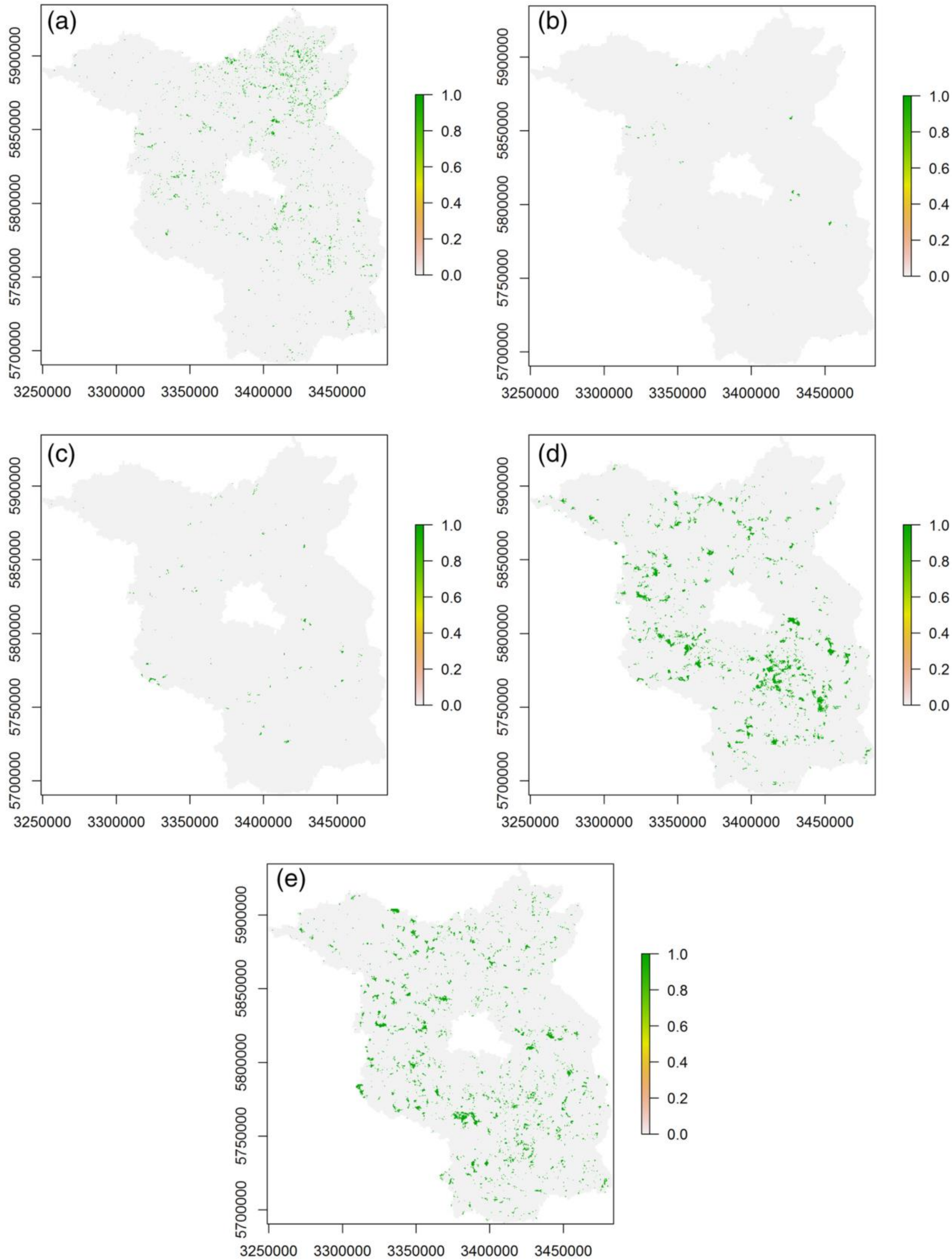

Figure IV. 3: Predicted collision risk areas for each of the frequently-hit bird-groups at WTs in the federal state of Brandenburg A. Buntings B. Crows C. Larks D. Pigeons E. Raptors

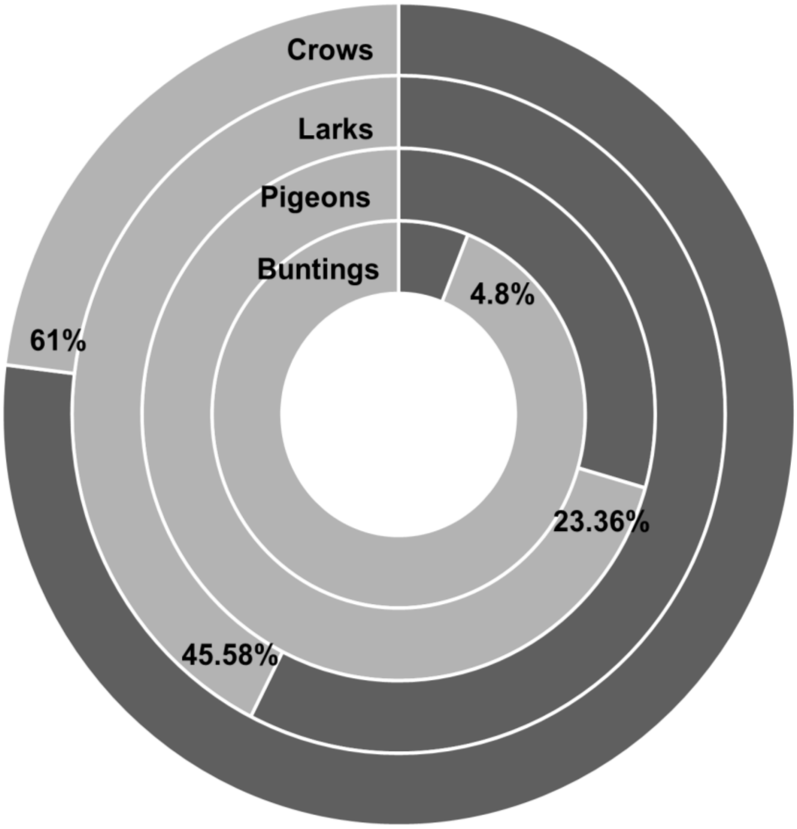

Figure IV. 4: The predicted collision risk areas; group wise overlaps between the Raptor collision risk space and that of the other frequently-hit bird-groups at WTs in the federal state of Brandenburg.

The raptor collision data showed broad coverage across the total collision space with every threshold criteria and also showed significant overlaps with the collision spaces of the other bird groups; the pigeons, larks, crows and buntings (shared approximately 23 %, 45 %, 61 % and 5 % of their respective collision space with that of the raptors; Figure IV. 4).

However, when the composite values were averaged across all groups to find areas where the collision probability = 0 (which suggested that it was very unlikely that a bird belonging to any of the five groups would collide with a turbine installed in this grid cell ~19,189 km^2), whereas when the collision probability = 1 (suggesting all the five bird groups had a high probability of collision with a turbine installed in this grid cell ~0 km^2). Higher values indicated higher collision probabilities for some, if not all, of the five groups, while lower values indicated that at least one species had a very low collision probability in this grid cell. For the threshold cut-off values; 2, 3, and 4, the expanses were approximately 10,038 km^2, 255 km^2 and 0.02 km^2, respectively, across the federal state (Table IV. 4).

	Overlaps	Overlapping collision risk area (*in km²*)
Bird-Groups	**None**	19,189.24
	2 Bird-Groups	10,038.47
	3 Bird-Groups	254.93
	4 Bird-Groups	0.02
	All	0

Table IV. 4: Expanse of the overlaps between the predicted collision risk areas (*in km²*); between the frequently-hit bird-groups at WTs in the federal state of Brandenburg

Similarly, (Figure IV. 5) the different probabilities of collisions (between 0 and 1) showed that the areas with probabilities of collision (with threshold; cut-off value >0.5) s also had a small expanse across the federal state (Table IV. 5), especially in the cases of crows, buntings and larks (contributed approximately 0.5 km^2 (0.9 %), 39 km^2 (0.13 %) and 150 km^2 (0.50 %), respectively, to the probable collision area). The raptors again showed the broadest coverage across the total collision space for this threshold; with approximately 3,054 km^2 (~10 %) and were followed by pigeons; with 945 km^2 (~3 %).

However, for the further probabilities (with threshold; cut-off value <0.5) the collision risks assessed in the region were relatively much lower, i.e. raptors, pigeons, larks, crows and buntings; contributed approximately 26,429 km^2 (~90 %), 28,536 km^2 (~97 %), 29,329 km^2 (~99 %), 29,305 km^2 (~99 %) and 29,419 km^2 (~99 %) across the state, respectively (Table IV. 5).

Out of these areas, only the areas (with threshold; cut-off values <0.05) could be categorized as areas with significantly lower probabilities of collision, i.e., with raptors, pigeons, larks, crows and buntings; contributing approximately 298 km^2 (~1 %), 2,273 km^2 (~8 %), 6,864 km^2 (~23 %), 14,149 km^2 (~48 %) and 4,555 km^2 (~15 %), respectively (Table IV. 5).

Moreover, the composite analyses for all the bird groups together and with each group paired with the raptors (Figure IV. 6 and Figure IV. 7, respectively) also identified areas with lower probabilities of collision (with threshold; cut-off value >0.5) on TIs in the state. These were averaged across all groups and still showed only a small expanse of 754 km^2, i.e. ~2 % of the area of the federal state (Table IV. 6 and Table IV. 7, respectively).

Bird-group	Collision risk range	Composite collision risk area (*in km²*)
	0-0.05	4,554.83
Buntings	**0-0.5**	29,418.96
	0.5-1	38.56
	0-0.05	14,149.14
Crows	**0-0.5**	29,305.3
	0.5-1	0.43
	0-0.05	6,863.89
Larks	**0-0.5**	29,328.68
	0.5-1	150.13
	0-0.05	2,273.24
Pigeons	**0-0.5**	28,536.35
	0.5-1	945.27
	0-0.05	297.52
Raptors	**0-0.5**	26,428.82
	0.5-1	3,054.9

Table IV. 5: Expanse of the predicted collision risk areas (*in km²*) for different collision risk ranges for the frequently-hit bird-groups at WTs in the federal state of Brandenburg

Composite collision risk range	Composite collision risk area (*in km²*)
0-0.2	**14,925.41**
0.2-0.4	**10,038.47**
0.4-0.6	**254.93**
0.6-0.8	**0.02**
0.8-1	**0**

Table IV. 6: Expanse of the predicted composite collision risk areas (*in km²*) for different collision risk ranges of the frequently-hit bird-groups (together) at the WTs in the federal state of Brandenburg

	Bird-group	Composite collision risk range	Composite collision risk area (*in km²*)
Raptors	**Buntings**	**0-0.2**	7,521.11
		0.2-0.4	18,136.38
		0.4-0.6	1,526.29
		0.6-0.8	0.57
		0.8-1	0.02
	Crows	**0-0.2**	9,915.36
		0.2-0.4	14,664.86
		0.4-0.6	405.19
		0.6-0.8	0.56
		0.8-1	0
	Larks	**0-0.2**	9,222.83
		0.2-0.4	16,550.52
		0.4-0.6	830.52
		0.6-0.8	4.15
		0.8-1	0.03
	Pigeons	**0-0.2**	5,784.76
		0.2-0.4	17,669.79
		0.4-0.6	3,673.95
		0.6-0.8	124.33
		0.8-1	0.11

Table IV. 7: Expanse of the predicted composite collision risk areas (*in km²*) for different collision risk ranges; between Raptors and other frequently-hit bird-groups at WTs in the federal state of Brandenburg

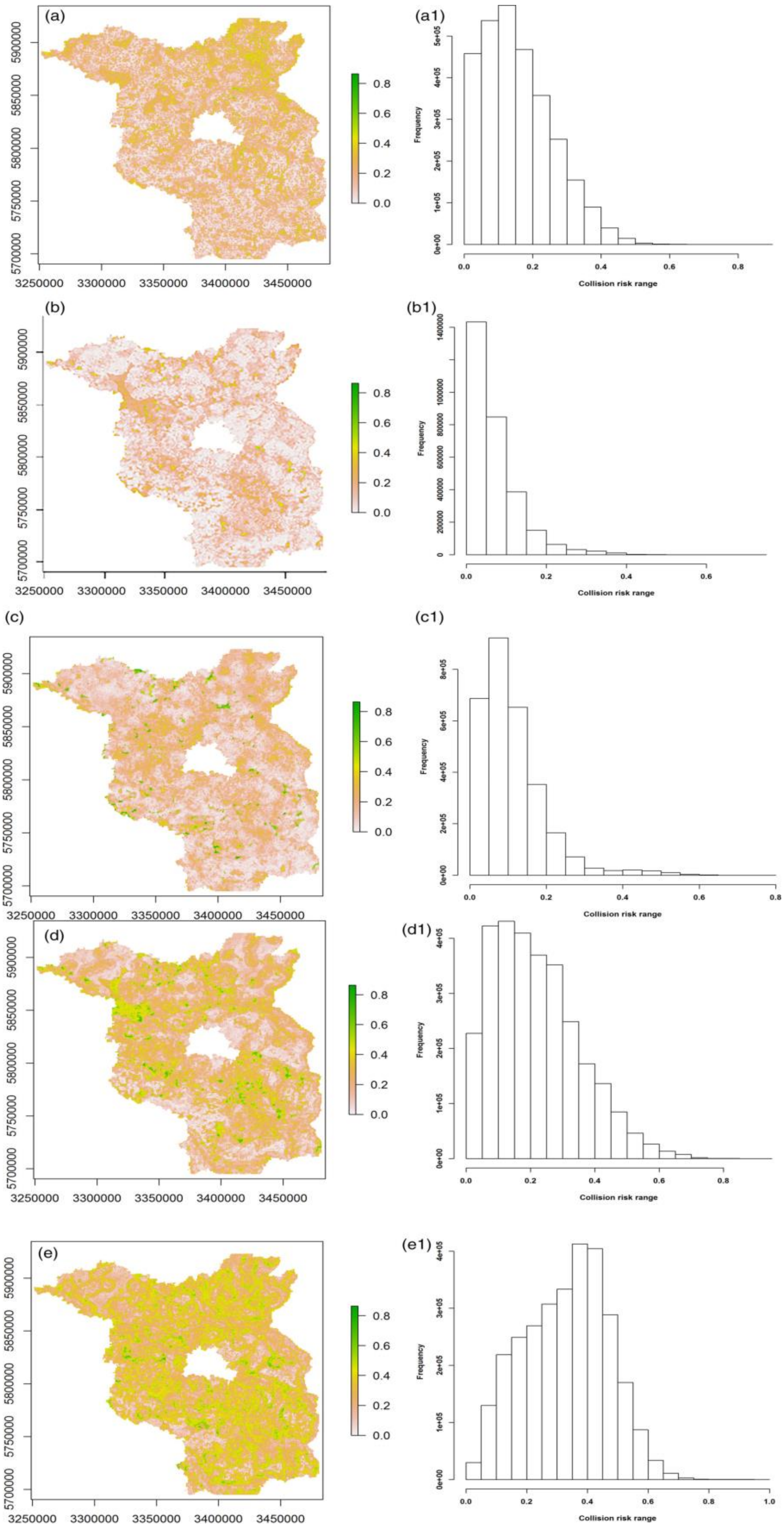

Figure IV. 5: Predicted collision risk areas; for different collision risk ranges at WTs in the federal state of Brandenburg, for the frequently-hit bird-groups along their entire collision risk range A. Buntings(A1) B. Crows(B1) C. Larks(C1) D. Pigeons(D1) E. Raptors(E1)

DELV[1]	Buntings	Crows	Larks	Pigeons	Raptors
B	15.7	17.6	16.2	20.8	24
F	13.7	12.2	14.5	15.3	23
FW	12.1	17.2	18.5	30.6	29
FF	17.5	14.5	18.5	23.6	21
GF	13.4	15.1	20.4	17.5	21.5
GAS	15.8	19.3	17.1	14.6	28
RA	15	16.9	18.5	18.3	23.5
SS	14.3	15.8	18.5	17.6	27
S	21.9	17.0	18.3	21	24
SB	18.4	14.5	17.7	18.8	22.5
SW	12	13.3	17.5	20.	22
W	13.8	13.9	17.2	18.4	24

Table IV. 8: Variable importance based on the mean decrease in accuracy for the cases of detected collisions at WTs for each of the frequently-hit bird-groups

¶ *Higher values of mean decrease in accuracy indicate variables that are more important to the classification*

[1]*Acronyms corresponding to the predictor variables are described in Table IV. 1.*

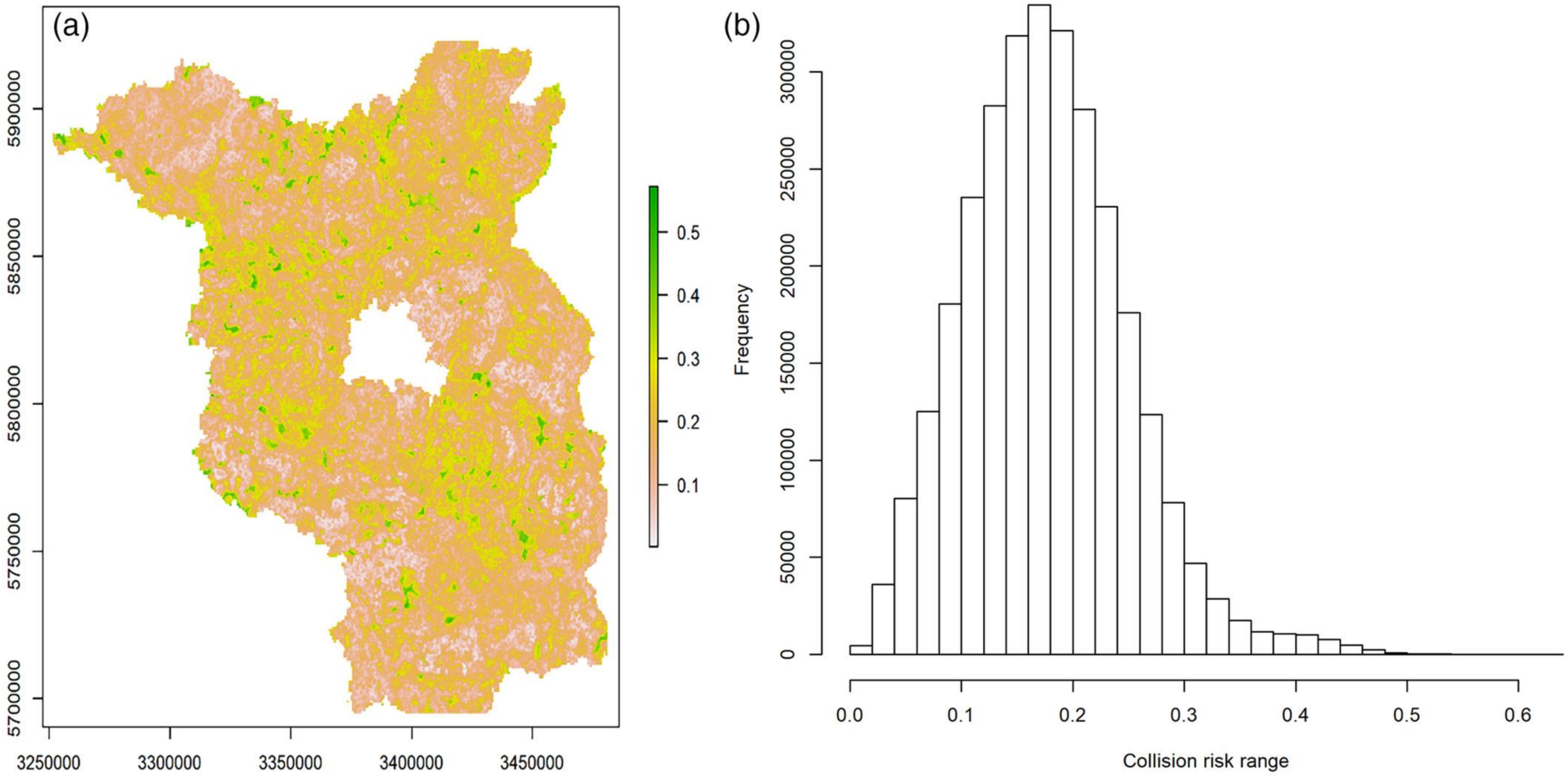

Figure IV. 6: Composite collision risk areas at WTs in the federal state of Brandenburg, for the five frequently-hit bird-groups along their entire collision risk range

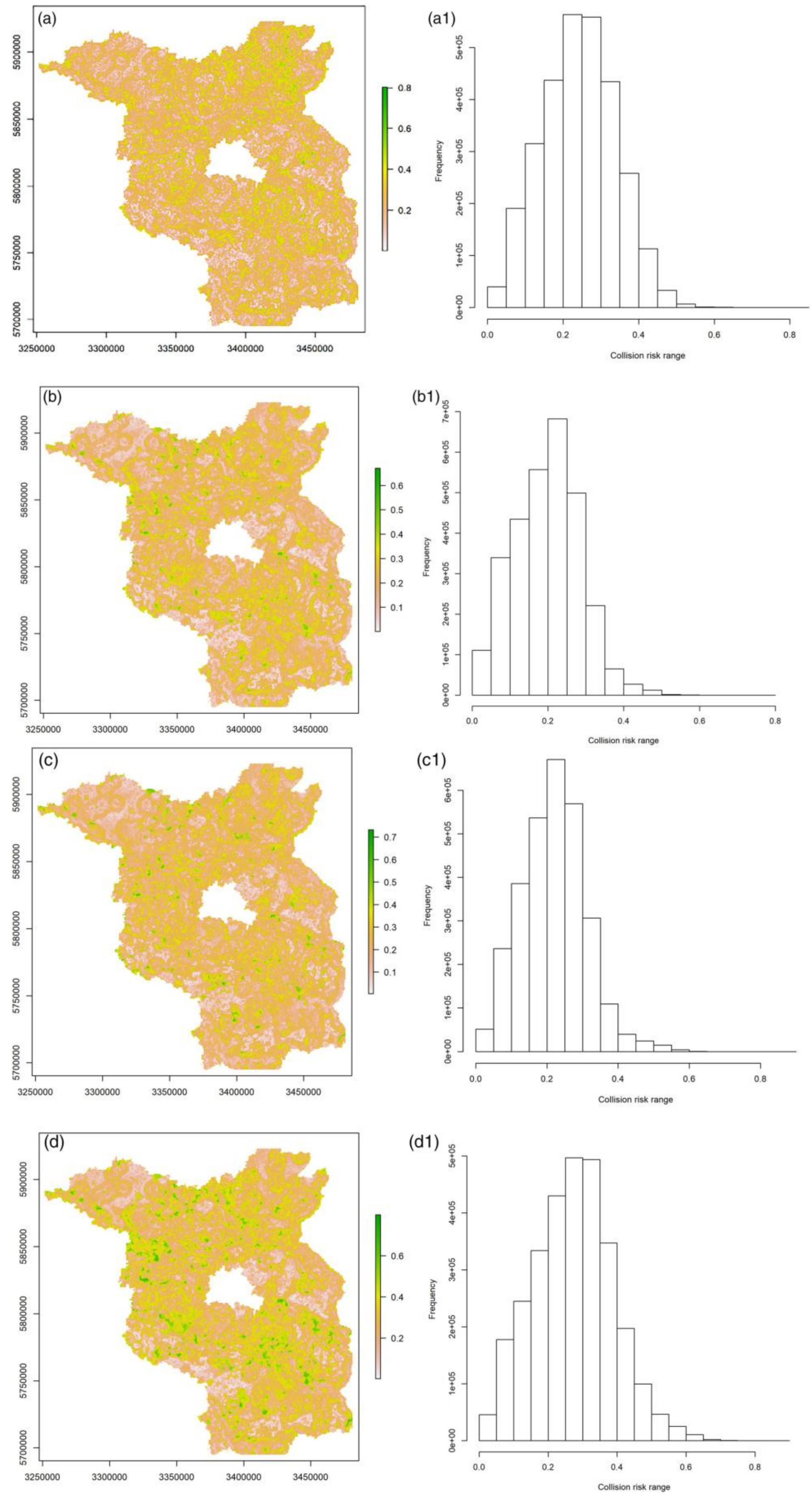

Figure IV. 7: Expanse of the composite collision risk areas; between Raptors and other frequently-hit bird-groups at WTs in the federal state of Brandenburg, showing overlaps along their entire collision risk range A. Buntings-A1 B. Crows-B1 C. Larks-C1 D. Pigeons-D1

Simultaneously, the RF algorithm also provided group-wise metrics of variable importance for the considered predictor DELVs, based on the descending in classification accuracy (Table IV. 6). The distances to the edges of the flowing watercourses and the distances to the edges of green and open areas outside human settlements were the parameters with the largest importance in predicting the possibility of collision by raptors on TIs. Their observed carcasses were detected at turbines situated from 2,500 meters onwards from the edges of the flowing watercourses and between 750-1,900 meters from the edges of green and open areas outside of human settlements. The collision probability for crows also showed sensitivity to the distance from the edges of green and open areas outside the human settlements, with higher carcass detections at turbines closer to their borders; detections were primarily observed at turbines situated between 1,000 meters and up to 1,500 meters to these borders. The distances to the edges of the shrublands and grasslands were also major determinants of bunting and lark collisions, respectively. The carcasses were detected near the wind turbines primarily situated at approximately 2,500 meters from the edges of the shrublands and between 250-750 meters from the edges of the grasslands and open areas, respectively. The distances to the edges of the flowing watercourses were also of very high importance for the prediction of the collision probability of pigeons, with their carcass detections at turbines situated from 2,500 meters onwards from the edges of flowing watercourses and at turbines between 100-1,000 meters from the edges of the forests and forested areas, (Table IV. 8). The distance distributions of these common predictor DELVs, for both; those where fatalities were registered and those where no fatalities were registered for each of the bird groups, could be used to represent the similarities among their predicted collision risk areas (Chapter VIII: Annex: Figure A2). These mechanistic relationships between the collision probabilities for the bird groups and the key sensitive distances from these particular land-use types can also be visualized according to the conditional density estimate plots with the discrete data (Falkowski et al. 2009) and the partial dependence plots (Friedman 2001) after RF analyses, respectively (Chapter VIII: Annex: Figure A3, A4, A5, A6 and A7).

Discussions

Our study demonstrates the identification of potential bird collision areas at WTs prior to installations by delineating the causes of collisions, via demonstrating the benefits of incorporating a species collision dataset as a proxy for species presence into species distribution models to make informed management decisions to combat biodiversity loss. In our study, a set of 12 independent distances to the edge-based land-use variables were used to analyse the spatial distribution of the wind turbines with registered collision fatalities. We limited the scope of our study to the frequently-hit bird groups within the geographical limits of the federal state of Brandenburg, Germany. This process was performed using random forest models; a machine learning algorithm that has increasingly wide usage in the environmental and nature conservation fields, such as climate change (Gaal et al. 2012), ecology (Cutler et al. 2007; Evans et al. 2011), forestry (Falkowski et al. 2009) and environmental remote sensing (Rodriguez-Galiano et al. 2011; Adelabu et al. 2014).

Since the data in our study was not collected systematically, the compilation only provided a rough indication of which birds are most frequently killed at the wind turbines. In our study, the approach of using the available binary collision response (0-1) data from each of the frequently-hit bird groups at WTs allowed the group-wise identification of potential areas with or without any collisions (binary response of 1 or 0, respectively; Figure IV. 3; Table IV. 3). Our approach also checked for subsequent overlaps, if any (Figure IV. 4; Table IV. 4). This was essential given the large birds were reported unproportionally often, likewise, the smaller birds went undetected often. Necessary overlaps could ensure the extension of conservation efforts across taxa. With respect to collisions at wind turbines specifically, raptors already have been the subject of maximum attention. These birds generally have low reproductive rates and any minor increase in mortality could have considerable consequences on their population sizes (De Lucas et al. 2012; Eichhorn et al. 2012; Ferrer et al. 2012; Schaub 2012; Bellebaum et al. 2013). Moreover, birds of prey are also already known to play a very important role as flagship and umbrella species within general nature conservation strategies, besides being critical ecosystem services providers themselves (Donázar et al. 2016). Raptors might also be used as indicators and/or umbrella species useful for evaluating and managing mitigation measures (Moleón et al. 2007; Pérez-García et al. 2011; 2016) in a rather prospectively changing ecosystem and landscape due to human interests i.e. planning new infrastructures for wind energy harness (Donázar et al. 2016) in order to minimize any undesirable effects. Regional models for conservation planning based on umbrella species have been often proposed to benefit many nontarget taxa in the world of conservation biology (Pruett et al. 2009). Therefore, with raptors already showing the greatest overlaps with all other frequently-hit bird groups, most likely due to their broad range covering the parameter space of the reference area, as well as their appreciably greater probability to be hit by the turbine structures and be detected afterwards owing to their bigger body sizes that have greater persistence times that are easier to detect (Bose et al. 2018; Table IV. 3). With raptors again showing the broadest coverage across the total collision space under higher collision probability thresholds (>0.5; Table IV. 5). Therefore, as an umbrella species, the raptor conservation should very well be given the highest priority, as nontarget plants and animals also benefit from these efforts.

Apart from this, our approach also enabled the simulation of areas with different collision probabilities (between 0 and 1; Figure IV. 5; Table IV. 5), i.e. areas from very low to very high chances of collisions on TIs, for each of the bird groups. In addition, the effects of the different land-use types on the collision sensitivity were also catalogued in the detected areas, which particularly highlighted the sensitive distances to these land-use types for each of the bird groups - that need to be avoided for future TIs. These distances are often required when policymakers ask for information to ensure safe deployment of WTs. Therefore, the results can be helpful for showing the increase and decrease of collision risk with specific proximities to specific land-use types, thereby proposing approximately safer placements of the WTs in the landscape. In cases where turbines have already been installed at these ascertained distances, our study allowed the identification of those turbines that might have the highest collision risks and where assessments of bird collisions and their population dynamics also become highly important for further understanding of the deleterious population-level effects of collisions that should be the focus of mitigation measures.

In the initial steps, a RF model was calibrated separately for each group with the available collision data to identify the collision risk areas within the limits of the federal state of Brandenburg. The analyses resulted in relatively acceptable OOB errors but misbalanced classification errors, which were unequally distributed between the pseudo-absence (majority class) and the presence (minority class) of the collision responses for every group (imbalances in the input response data for each group).

Despite these disproportionate predictions, the calibrated RF models were still considered robust and logical because of the minimal OOB errors, in combination with the higher classification errors for the minority classes and the negligible classification errors for the dominant classes (Evans et al. 2011). This resulted in the over-representation of the dominant class, while leading to the underestimation of the minority class, primarily due to the bootstrapping procedures used in the RF models. Therefore, the resulting RF models considered the presence (minority) class and intends to attenuate the overall rate, thereby resulting in very good prediction accuracy (Gaal et al. 2012).

The analyses for the relative importance of the considered DELVs on the group-wise collision response indicated that the distances to the edges of the flowing watercourses were the most important indicators for collision in the classification process for raptors (Chapter VIII: Annex: Figure A7). The partial plots available for this particular DELV on a logit scale gave the probability of collision across its distances. According to which there was a higher risk of collision at distances farther than 2500 meters from the edges of the flowing watercourses, at shorter distances the risk was much lower because thermal convection generally does not develop over large bodies of water, which typically makes raptors detour around large bodies of water (Meyer et al. 2000; Alerstam 2001; Meyburg et al. 2002; Bildstein et al. 2009). Furthermore, the distances to the settlements and structures and to the green and open areas around these structures also proved to be of very high importance in the classification process of the raptors and crows as well (Chapter VIII: Annex: Figure A4, A7). This aligned with literature regarding their respective affinities for the urban environments. Their observed carcasses were at the turbines closer to their borders, because raptors and crows are highly abundant in open areas at the fringes of infrastructures and settlement zones (Benitez-Lopez et al. 2010), primarily due to the availability of adequate hunting options (Dean and Milton 2003) of especially many human-commensal small mammals (Mannan and Boal 2000; Millsap and Bear 2000; Ranazzi et al. 2000) and the availability of roadkill carrion (Lambertucci et al. 2009). They have also been observed using the features of the urban landscape, such as trees, fences and buildings adjacent to open areas around settlements particularly, as shelter from the wind and domestic predators and as a concealment for ambush attacks on their prey, as perches and as new and artificial nesting substrates. (Chace and Walsh 2006; Rutz 2006; Roth et al. 2008; Hogg and Milon 2015).

Concerning crows, food is the most important anthropogenic resource driving the increase in corvids near settlements, where the birds forage for invertebrates, roadkill, nestlings, small mammals, berries/fruits/seeds, and anthropogenic food items. When corvids nest within 1 km of settlements and campgrounds, they ultimately increase their reproduction and survivorship (Marzluff and Neatherlin, 2006). The partial plots for this bird group showed that the risk of collision increased with increasing distances (>1,000 meters) from the edges of the settlements and structures but decreased at distances farther than 1,500 meters. Pigeons on the other hand (Chapter VIII: Annex: Figure A6), also abundant in the built-up environments have also adapted their nesting requirements and foraging habits to be conducive to urban lifestyles (Harris et al. 2016). Especially in urban areas surrounded by forest/water landscape types (Hetmański et al. 2010). Their partial plot showed a higher risk of collision at distances closer than 1 km from the edges of forests and forestry areas than at greater distances.

Likewise, the distances to shrub-lands and grasslands were the major determinants for the collision risk of the buntings and larks, respectively (Chapter VIII: Annex: Figure A3, A5). The partial plots for Buntings exhibiting higher collision risks at approximately 2,500 meters distances from the borders of shrub-lands. Buntings being shrub-land birds, prefer large intact stands over small stands with larger habitat-edge rations (Rudnicky and Hunter, 1993; Rodewald and Vitz, 2005). Larks on the contrary show affinities to pastures, grasslands and open landscapes, avoiding tall, dense vegetation cover, nesting and foraging in open agricultural fields (Donald et al. 2001; Eraud and Boutin 2002; Morris et al. 2004). Their partial plots showed higher chances of collision on TIs between 250-750 meters from the edges of the grasslands and open areas.

The predicted potential collision risk areas (Figure IV. 3; Table IV. 3) in total had a relatively negligible and a highly dispersed expanse that totalled to merely 2,130 km^2 area of the vast 29,479 km^2 area of the federal state. The raptors contributed to approximately 35 % of the total and all bird groups shared an appreciable proportion of their respective collision spaces with that of the raptors (Figure IV. 4). However, when values were averaged across the entire detected collision risk areas for all the bird groups, the areas where birds belonging to any of the five groups would collide with an installed turbine comprised of approximately 19,189 km^2 across the state, whereas there was no scenario where all five groups would have a high probability of collision together (0 km^2). Higher grid cell values indicated higher collision probabilities for all five groups, while lower values indicated that at least one species, if not more, had a very low collision probability (Scenarios; 2 bird groups, 3 bird groups, and 4 bird groups, respectively, had expanses of approximately 10,038 km^2, 255 km^2 and 0.02 km^2 across the federal state; Table IV. 4).

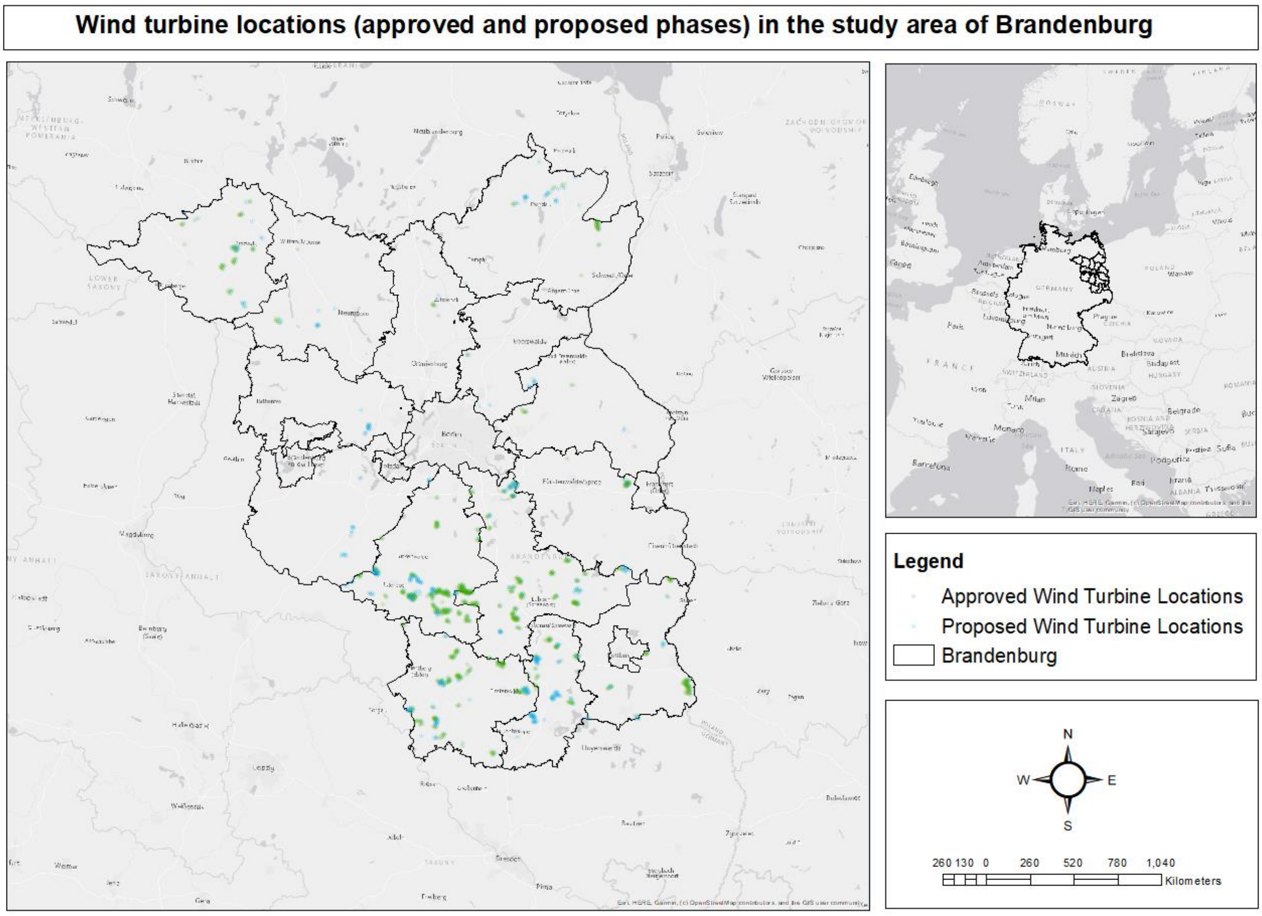

Figure IV. 8: Study area showing the spatial locations of all the approved and proposed wind turbines (to be installed phase)

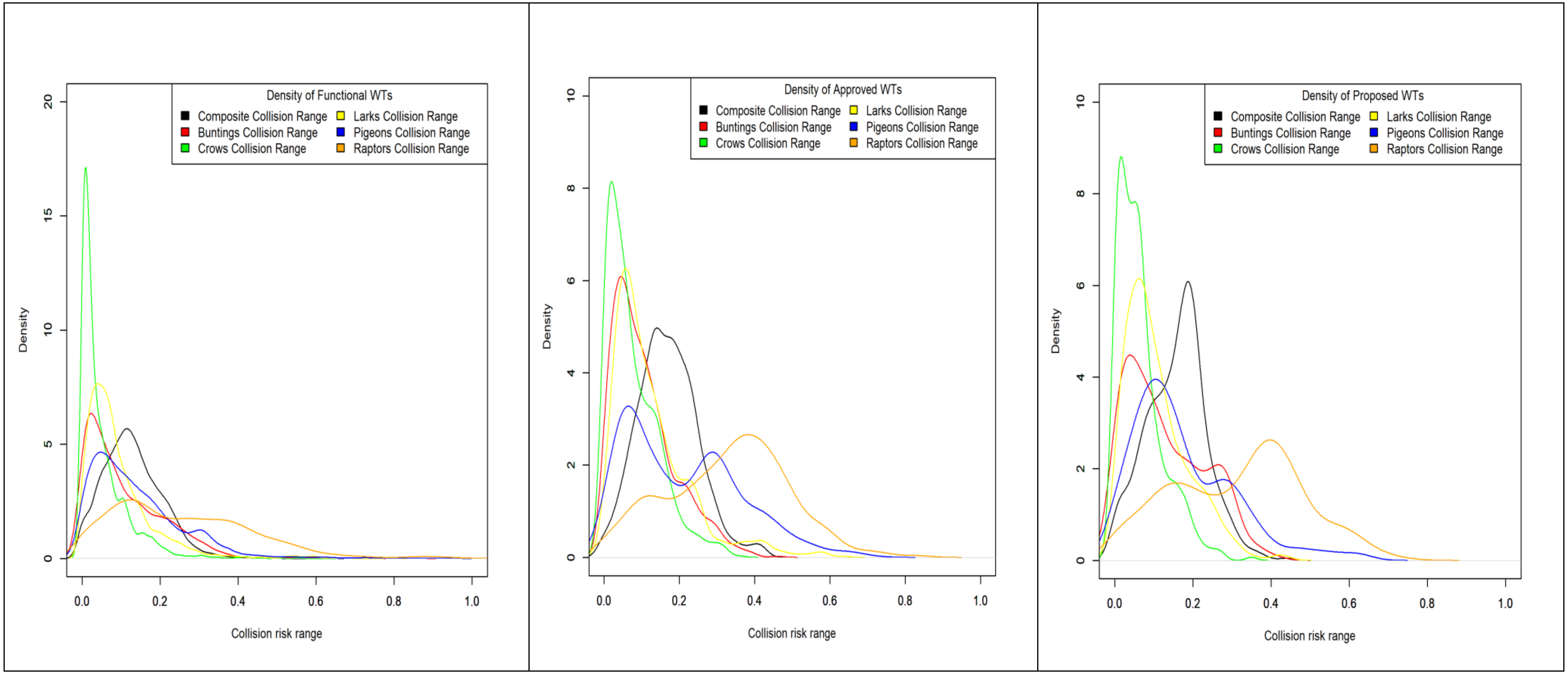

Figure IV. 9: Density distribution of the functional wind turbines (existing), approved and proposed wind turbines (to be installed) along the entire predicted collision risk range of the frequently-hit bird-groups in the federal state of Brandenburg (individually and composite)

Similarly, different probabilities of collisions (between 0 and 1) showed that the areas with higher probabilities of collision (threshold; cut-off value > 0.5) on TIs also had a negligible expanse across the federal state (Table IV. 3). The raptors again showed the broadest coverage across the total collision space under this threshold, with approximately 3,054 km^2, followed by pigeons, with a risk area of 945 km^2.

However, for the lower probabilities (threshold; cut-off value <0.5) the associated collision risk areas were relatively small; with raptors, pigeons, larks, crows and buntings contributing approximately 26,429 km^2 (~90 %), 28,536 km^2 (~97 %), 29,329 km^2 (~99 %), 29,305 km^2 (~99 %) and 29,419 km^2 (~99 %) across the state, respectively.

Out of these areas, only the areas with collision probabilities below 0.05 (threshold; cut-off value <0.05) could be assessed as areas with significantly lower probability of collision. Of these areas, raptors, pigeons, larks, crows and buntings contribute approximately 297 km^2 (~1 %), 2,273 km^2 (~8 %), 6,864 km^2 (~23 %), 14149 km^2 (~48 %) and 4,555 km^2 (~15 %), respectively. But as long as the probability of collisions were above the 0.05 threshold, there was some risk of collision, even if the risk was low (Figure IV. 5; Table IV. 5).

Among the turbines, some of the existing turbines were already distributed in the predicted collision risk areas; where the risk was below the threshold of 0.5 for each of the bird groups, along with some wind turbines in the approved and proposed phases of construction also planned in these areas of the state (Ministry of Environment, Health and Consumer Protection for the state of Brandenburg; LUGV, 2014).

The areas where these turbines were distributed narrowly approached the collision risk areas that had higher probabilities of collision (threshold >0.5), especially for pigeons and raptors (Figure IV. 8 and Figure IV. 9). The expansion has already (through approved turbines) led to and will continue (through proposed turbines) to lead to a further increase of risk, although under a given threshold. The turbines in areas with fairly lower collision probabilities could also lead to non-negligible numbers of collisions, but only the areas with collision probabilities <0.05 can be interpreted as the actual “no risk areas”, and all other probability thresholds do have some risk or at least a residual risk of collision.

Our results illustrated that the wind-based renewable energy targets set for the federal state of Brandenburg could be achieved by suitably positioning the wind turbines. To avoid the predicted collision risk areas to minimize bird collisions at the WTs, they should be positioned particularly avoiding sensitive distances from the land-use types with the highest detected risk levels.

Additionally, our results also identified existing wind turbines that have already been installed at these ascertained distances. However, as we can see from the probability distributions, the hazard level that might increase by the placement of some of the approved and proposed turbines in these areas. Therefore, planning of future installations must be performed with utmost vigilance.

Our study also allowed the identification of the turbine locations that might already have higher collision risks due to their existing installations at sensitive distances. Our findings are particularly relevant for planners and policy makers. The differential response of the reported birds suggest that it is possible to also locate wind farms and to plan changes in land use in accordance with conservation interests.

Depending on regional conservation priorities, it may also be possible to locate suitable wind turbine sites that might only affect species of lower conservation concern or specifically benefit those in need of conservation action or extended protection across non-target species by extending suitable conservation actions to only the umbrella species. Furthermore, consideration must also be given to the ecological role of the species from a wider ecological perspective, along with assessments of their population dynamics. This would further our understanding of the deleterious population-level consequences while designing suitable mitigation measures.

Therefore, the authors would still like to clearly and understandably state that despite the usefulness of their study for regional planning processes, the assessed collision distributions are not a substitute for detailed population level monitoring nor for site-specific Environmental Impact Assessments Studies (EIAs) in the course of project planning.

The best approach is not to expect our models to be an ultimate endpoint but instead to follow it as a guide for consultation within limited resources and should not be used as a sole decision-making tool for the selection of suitable wind turbine sites in the federal state.

Chapter V: Predicting strike susceptibility and collision patterns of the Common Buzzard (*Buteo buteo*) at wind turbine structures in the federal state of Brandenburg, Germany

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Abstract

With the increase in wind turbines, bird collisions have developed as a potential hazard. In the federal state of Brandenburg, Germany, despite the on-going mitigation efforts of increasing the distances of wind turbines from the breeding areas of the more severely affected populations of red kites (*Milvus milvus*), the additional detrimental influences on the buzzard populations (*Buteo buteo*) have added to the challenges for wind power expansion. Using data on the regional distribution of the buzzards, along with their carcass detections around the wind turbines (WTs), we aimed to better understand their collision distribution patterns in relation to their habitat use patterns to predict their exposure to collision risk using boosted regression trees (BRTs). Additionally, we integrated the developed collision potential map with the regional density map of buzzards to identify areas of increased strike susceptibility in turbine installations. Our study showed that the buzzard collisions were primarily concentrated at the turbines situated at sensitive distances from the edges of watercourses (>1000 meters), as well as those along the edges of grasslands (>750 meters), in the green open areas around/areas with minimal settlements (750 meters-1750 meters), and along the edges of bushlands (>1500 meters), together explaining 58% of the variance in their collision distribution. Conclusively, our study is applicable to conservation because it demonstrates the identification of potential collision areas along with the causes of the collisions, in addition to demonstrating the benefits of incorporating a species collision dataset as a proxy for species presence into species distribution models to make informed management decisions to eventually combat biodiversity loss.

Keywords: wind energy; bird carcass monitoring search operations; land use types; collision potential; strike susceptibility; landscape planning; boosted regression trees (BRTs)

Introduction

Brandenburg is of particular interest in the context of Germany's ambitious aims of transforming energy production towards modes of renewable energy generation in the coming decades (Moeller et al. 2014). With the aim of reducing CO2 emissions by 80-95% by the year 2050 compared to the level in 1990, the interim target is a 40% reduction by 2020, coupled with a share of 35% from renewables (BMU, 2010; Meyerhoff et al. 2010). In Brandenburg, wind energy in particular has been increasingly explored as a main source of renewable energy, leading to the widespread construction of wind farms in the state. On the other hand, this growing production of wind energy has been accompanied by the emergence of new conservation issues, in particular, the collision of birds through direct impacts with the turbine structures (Dewitt et al. 2006; Carrete et al. 2009; de Lucas et al. 2012; Martín et al. 2018; Tikannen et al. 2018; Watson et al. 2018). The mortality due to direct collisions has been identified as a major threat, especially for the large, soaring raptors, being most prone and vulnerable to collision (Krone and Scharnweber, 2003; Langston and Pullan, 2003; de Lucas et al. 2004; 2008; Beston et al. 2016). In addition, these species are also characterized by long generation times and low reproductive rates, making them highly sensitive to any increase in mortality (Sæther and Bakke, 2000). Several studies on the demographic effects of wind turbine fatalities have revealed that mortality due to wind turbines may reach levels that can threaten local populations, e.g. the Egyptian Vulture (*Neophron percnopterus*) in southern Spain (Carrete et al. 2009), the Golden Eagle (*Aquila chrysaetos*) in the USA (Hunt, 2002), and the Red Kite (*Milvus milvus*) in Germany (Bellebaum et al. 2013). Apart from this, the indirect effects; by means of the loss of nesting and foraging habitats add to the conservation concerns (de Lucas et al. 2007).

Wind energy in Brandenburg to be specific, has already had the highest energy capacity amongst the other installed renewables in the state (LBV, 2010; EEG-Anlagenregister, 2011; Der NEP, 2012; LBV, 2012; The windpower, 2012; Twele et al. 2012). However, with the increase in the numbers of wind turbines, the mortality of birds from collisions has simultaneously developed as a potential hazard in the state as well (Grünkorn et al. 2009; Dürr, 2011; Eichhorn et al. 2012; Bellebaum et al. 2013; Grünkorn et al. 2016; Grünkorn et al. 2017). Moreover, it is becoming increasingly difficult to identify suitable sites for installations of additional turbines in the region as the saturation point has already been achieved (Walker, 2010). Therefore, the deployment of additional wind turbines in the state requires precise predictions of the bird strike susceptibilities to reduce bird collisions.

Over recent decades, environmentalists and managers have normally argued against the installation of wind farms in areas with high densities of birds. They make the simplistic assumption that the higher the abundance of individuals of a given species is at a particular site, the higher their susceptibility for collision with wind energy structures installed at that particular site (de Lucas et al. 2005; Carrete et al. 2012). This assumption has been readily challenged by many researchers, since their findings show that the pre-construction bird abundances and the observed numbers of carcasses as a measure of the post-construction bird collisions through detections are not closely related (de Lucas et al. 2008; Ferrer et al. 2012; Tikkanen et al. 2018). The German State Bird Conservancies have also additionally developed recommendations in terms of the distances of wind turbines to such important bird areas as well as to the breeding sites of different species of birds (LAG VSW, 2015). In general, turbine site selection follows these recommended minimum distance of wind turbines to the breeding areas of sensitive bird species based on species-specific telemetry studies, collision data, spatial functional analyses, long-term observations and expert assessments (LAG VSW, 2015). Researchers also recommend a range of verification distances around wind farms that take into account areas in which there could be a high probability for a bird species to occur. These spaces can be derived from flight corridors, preferred hunting grounds of juveniles and breeding adults, roosting sites, certain landforms that cause favourable thermal conditions or other significant habitats for the species (LAG VSW, 2015).

For the federal state of Brandenburg, a major challenge for further expansion of wind energy production has been their negative effects on the breeding populations of red kites (*Milvus milvus*); Bellebaum et al. 2013; applied a model based on systematic searches for collision carcasses around wind turbines and estimated that in Brandenburg, at least 308 red kites are killed annually due to collisions with their structures alone. With more than 50% of the world population found here, Germany has a greater national responsibility for their conservation than for that of any other bird species (Dürr and Langgemach, 2006; Dürr, 2009; Bellebaum et al. 2013). However, in Brandenburg, in addition to the red kites, other species also have a high conservation importance, e.g., the lesser spotted eagle (*Aquila pomarina*), great bustard (*Otis tarda*) common buzzard (Buteo buteo), and the white-tailed sea eagle (*Haliaeetus albicilla*) (LAG VSW, 2015).

While the distance-based recommendations may help to protect spatially restricted species populations, the challenges differ for species like buzzards; because unlike their counterparts, buzzards occur almost everywhere in the state, making future turbine installations in Brandenburg particularly challenging (Weinhold, 2016).

Therefore, to develop conflict reduction strategies for a wide-ranging species, we examined the collision potential and the strike susceptibility of buzzards across the state. Using the ensemble method of boosted regression trees (BRTs), which is a combinational algorithm based on statistical and machine-learning techniques, that has relatively recently been applied to the world of species distribution modelling (De'ath, 2007; Elith et al. 2008). First, we used this method to develop a spatially explicit collision distribution model for the species across the state by means of long-term carcass data detected around turbines in relation to distances to different land use types. With buzzards occurring almost everywhere in the state, the purpose of this study was also to identify distances of wind farms to different land use types where there is a particularly high risk of collision. Second, these critical areas were further compared to the regional densities of buzzards to generate an actual strike susceptibility model across the study region.

We expect our strike susceptibility model to be applicable at the turbine deployment sites and our working methodology to be applicable only for a case-by-case review, taking into account the different land use types, their included features, the distances to the edges of these features and detailed information regarding the target species. Since the study predominantly focuses on buzzards and only on "direct" collisions with the wind turbine structures, it captures only one of the many ecological impacts of wind energy infrastructures. Therefore, the authors would like to clearly and understandably state that despite the usefulness of their study for regional planning processes, our collision distribution and strike susceptibility models are neither a substitute for detailed population monitoring nor for site-specific Environmental Impact Assessments (EIAs) in the course of project planning and while interpreting the results of our study and it is highly necessary to adjust our recommendations made for buzzards according to the specific situations present in different study regions and to the specific situations present in these study regions. The best approach is not to expect our models to be an ultimate endpoint but instead to follow it as a guide for consultation within limited resources and should not be used as a sole decision-making tool for the selection of suitable wind turbine sites in the federal state.

Materials & methods

Study area

The federal state of Brandenburg in north eastern Germany covers an area of 29,500 km^2 (Figure V. 1A) with a population density of only 85 people per km^2 (Moeller et al. 2014). Brandenburg has a currently installed wind energy capacity of 5.5 GW (Ender, 2015) and is regarded as the world's apical region for wind energy development (Quitter, 2010; Walker, 2010). Over recent decades, wind energy development has been rapidly paced in the state, driven by economic imperatives and aided by the sparse population density, which has led to the widespread construction of wind farms. WT structures have contributed substantially to the landscape of Brandenburg and have subsequently emerged as a new cause of bird loss (Dürr, 2014; Bose at al. 2018).

Carcass search data

Spatially limited, non-uniform carcass search data of birds were available from 69 of the existing 562 windfarms (Mean: 5 functional turbines per windfarm, excluding the dismantled windfarms and wind turbines) in parts of the study region for the period 2000 to 2015 (Bellebaum et al. 2013; Bose et al. 2018). From the 122 detections of exclusively buzzards, from the total number of carcasses detected, the spatial coordinate information of only these specific turbines, that reported the casualties was extracted for the purpose of our study. All carcass detections were limited by spatiotemporal inconsistencies related to researcher efficiencies due to the biases associated with the persistence times of the carcasses across the varieties of substrates (Erickson et al. 2014).

The largest influence although came from the differences in monitoring efforts, which ranged from only one control to many frequently and regularly controlled turbines (Bose et al. 2018) (Figure V. 1B).

The pseudo-absence data were also biased by similar fallacies but were still numerically dominant over the presence data available across the controlled wind farms. Therefore, for the purposes of our study, we down-sized the pseudo-absence data and excluded the carcass search detections of birds belonging to the same taxonomic family as that of buzzards (i.e. Accipitridae) using the spatial coordinate information only from the turbines with detections of other bird groups, making neither the presence nor pseudo-absence data dominant over the other. We also ignored the estimated numbers of birds discovered in each detection and solely used the spatial coordinate information of each of the turbines where the carcasses were detected.

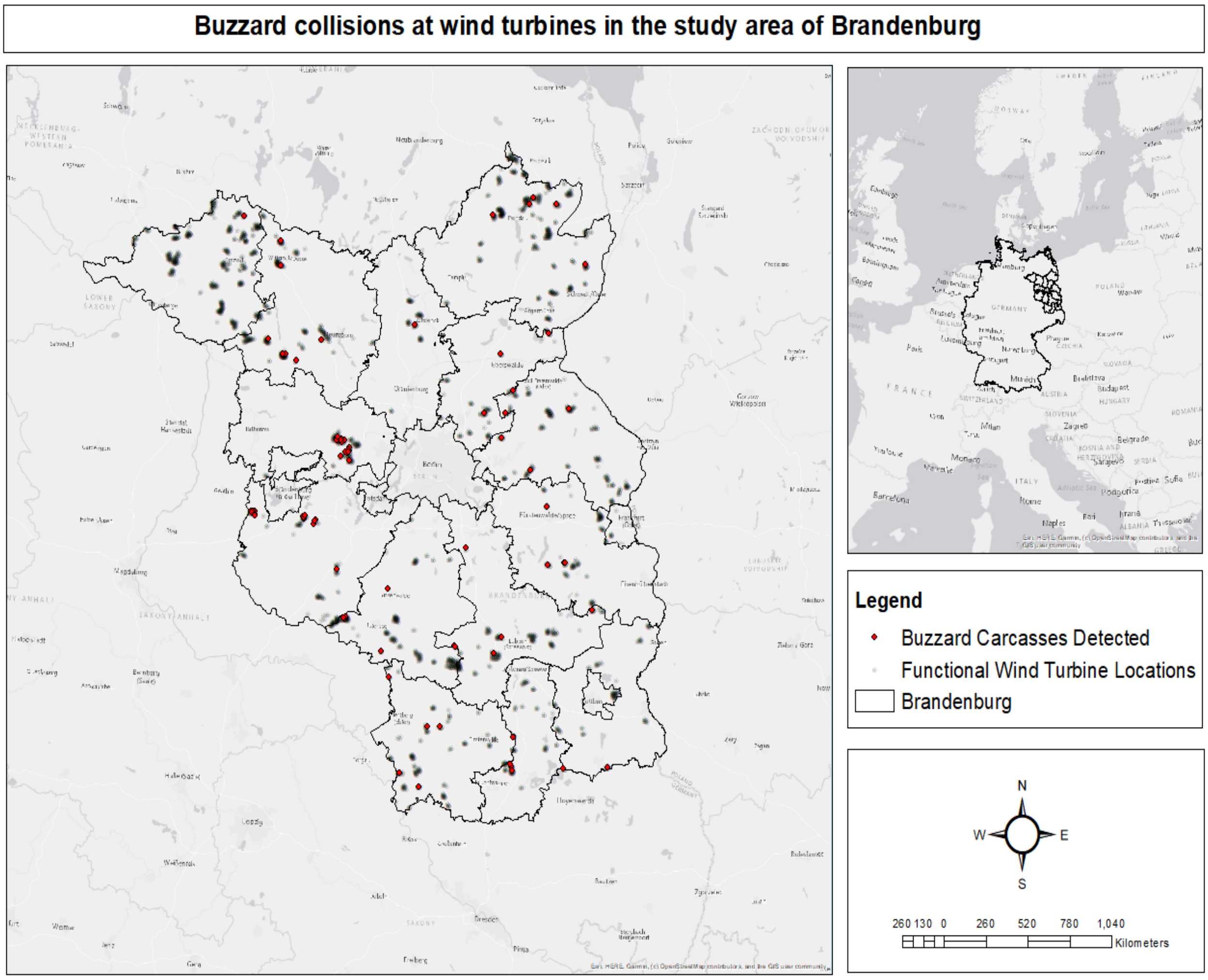

Figure V. 1A: Spatial locations of functional wind turbines and the wind turbines with detected Buzzard collisions in the study region of Brandenburg, Germany.

Carcass search data

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Distance to edge-based land-use variables (DELV)

The detailed database of land use data provided by the Biotope Type and Land Use Mapping Project of the State of Brandenburg of 2011 (BTLNK, 2011) was processed using the included features in the 12 major land use classes (Table V. 1) to avoid the greater degrees of inconsistencies and lack of information associated with the successive subordinate classes (Bose et al. 2018; Chapter VIII: Annex: Figure A1). The different types of land use classes were separated; the features of each of the individual land use class were transformed to polylines and pre-processed individually to create Euclidean distances at a cell resolution of 100 meters for the whole study area with ESRI-ArcGIS version

10.1. A resolution of 100 meters was chosen to find a compromise between accuracy, the size of the raster maps, and the available computer memory or processing time. Additionally, recommendations to policymakers are rarely based on data with a resolution below 100 meters. For ease of interpretation, the created Euclidean distances were given either a negative or a positive sign to denote the distances inside and the distances outside, respectively, of the feature of a particular land use class (Bose et al. 2018). Distance distributions of turbines under the functional wind turbine (pre-existing/with buzzard collision events/without buzzard collision events), approved and proposed wind turbine (to be installed) categories along the 12 DELVs under consideration (Chapter VIII: Annex: Figure A9).

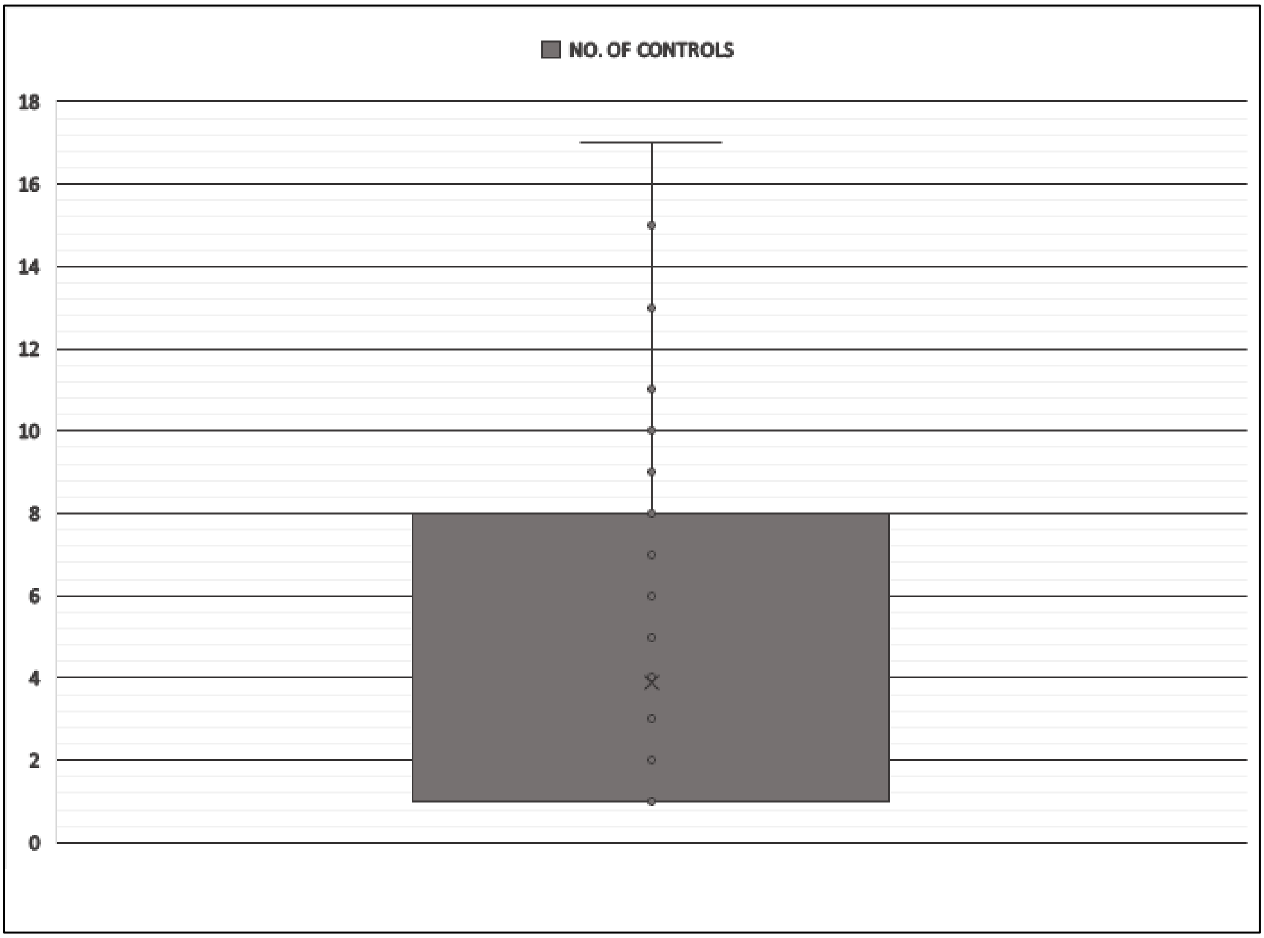


Figure V. 1B: Number of controls per the assessed wind turbines in the study region of Brandenburg, Germany.

VARIABLE	DESCRIPTION	COVERAGE (%)	VARIABLE ACRONYM
Bushlands	Deciduous bushes, field bushes, tree-lined roads, tree groups and riparian woods	**0.79**	**B**
Fields	Plow lands, arable lands and other farmlands	**35.11**	**F**
Forests_forestry	Forests and commercial forests	**35.51**	**FF**
Flowing_watercourses	Streaming waters, springs, small flowing rivers and channels	**0.39**	**FW**
Green_areas_settlements	Biotopes of green areas and open spaces including parks, gardens and village greens	**1.66**	**GS**
Grass_forbs	Meadows, pastures, grasslands, lawns and forb areas	**16.37**	**GF**
Ruderal_areas	Anthropogenic raw soil sites and ruderal areas with or without very few vegetation	**0.26**	**RA**
Shrublands	Dwarf shrubs, heathlands and conifer bushes	**0.35**	**S**
Special_biotas	Special biotopes including valleys, plantations, commercial gardens and tree nurseries	**0.87**	**SB**
Settlements_structures	Buildings, roads, paths, traffic and industrial areas, railroads and village like developments	**5.73**	**SS**
Still_watercourses	Still waters, lakes, small waterbodies, reservoirs, ponds and mine waters	**2.21**	**SW**
Wetlands	Mosses, swamps, sedges and peat cutting sites	**0.73**	**W**

Table V. 1. Distance to edge-based land-use variables (DELVs) used as predictors in the Federal State of Brandenburg, Germany.

Boosted Regression Trees

For the explanation and predictions of the collision patterns of the buzzards at wind turbines (WTs) against the distances of the turbines to the edges of various land use types, this study utilized the ensemble method of boosted regression trees (BRTs). BRTs is a machine-learning technique and builds on the concepts of decision trees and gradient boosting (Friedman, 2001; Elith et al. 2008; Hastie et al. 2011). BRTs have recently gained popularity due to several advantages over traditional, frequentist statistical methods (Heuck et al. 2019). They offer high predictive accuracies and good interpretability of results, do not tend to overfit (Dormann et al. 2013), are robust against missing data and collinearity of predictors, and are able to handle non-linearity and interaction effects (Friedman, 2001; Elith et al. 2008; Hastie et al. 2011)

Our response variable was the buzzard collisions, which were measured as the presence/pseudo-absence of buzzard carcasses around the wind turbine structures and the presence and detections of other birds through the carcass search (belonging to the taxonomic family of Accipitridae) around wind turbine structures as pseudo-absence data. Our predictor variables were the distances of the wind turbines to the edges of the 12 major land use classes considered (Table V. 1; Chapter VIII: Annex: Figure A1).

BRTs consist of two algorithms: regression trees (models that relate the response to the DELV predictors by recursive binary splitting) and boosting (adaptive method combining many of the simple models fitted iteratively in a forward stage-wise fashion to give improved predictive performance) (Elith et al. 2008). Four parameters are important for calibrating BRTs: (*bg*) bag fraction, (*tc*) tree complexity, (*lr*) learning rate, and (*nt*) number of trees. The bag fraction specifies the share of data that is randomly withheld while fitting the model (i.e., each single tree), thereby introducing stochasticity and avoiding overfitting. The tree complexity defines the maximum order of interactions between predictors in each single tree. The learning rate reduces the contribution of each single tree to the entire model and can be interpreted as a penalizing parameter. The number of trees determines the number of single decision trees included in the model and represents the model complexity (Torres et al. 2013; Heuck et al. 2019).

We used the dismo package (Hijmans et al. 2013) in R (R Core Team, 2017) to implement our model and the function gbm.step, with the (*tc*) fixed at 12 (equivalent to the number of predictor variables; DELVs), the (*lr*) varied between 0.05 and 0.0005, and a default (*bf*) of 0.5 (Friedman 2001) to fit the models, ideally, at least 1000 trees were performed, as recommended by Elith et al. 2008 was used along with the custom code (Elith et al. 2008) to generate BRT models of the collision potential for buzzards across the federal state. The model fit and predictive performances were balanced to reduce overfitting by jointly optimizing the *nt, lr,* and *tc* (Elith et al. 2008).

To determine the optimal number of DELVs that contributed to the response, we first ran a full model with all 12 DELVs in which a relative importance was assigned to each predictor DELV. Second, we ran another simplified model with only the highly contributing DELVs from the full model (optimal set), followed by an assessment of the response against each of them individually. We compared the goodness of fit among the models and evaluated the goodness of fit of our models using 10-fold cross-validated ROC AUC values (Receiver Operating Characteristic Area Under the Curve). (Fawcett, 2006), and the percent deviance in the cross-validation (*CVdev*) was also explained (Buston and Elith, 2011; Torres et al. 2013) for the full and the simplified models.

We further assessed the influence of each predictor in explaining the collision patterns by calculating their relative importance in the model (number of times a variable is selected in a tree, weighted by the squared improvements, and averaged over all trees; Friedman, 2001). Finally, we predicted the collision potential map for the entire study area using the model. The predictive map of the collision potential of the buzzards at the WTs (CP) was generated using the simplified model against the optimal set of DELVs. The predictive score of the collision potential ranged between 0 and 1 for each grid, according to the DELV characteristics of the grid cell and the model's fitted functions. The predictive maps were validated using the test data, and their predictive capacity was determined using the AUC, sensitivity (true positive rate), and 1-specificity (false positive rate) (Torres et al. 2013).

Regional Breeding Pair Density and Strike Susceptibility

The regional density atlas of buzzards (Ryslavy et al. 2011) was used to assess the areas of higher strike susceptibility within the assessed potential collision zones. The density map represented the number of breeding pairs (BPs) of buzzards in terms of 6 classes (i.e., BP). 1 BP, 2-3 BP, 4-7 BP, 8-20 BP, 21-50 BP, 51-150 BP) based on the paper sheet contour system of the topographical maps TK25 (DTK25-V, 2014). Most areas in Brandenburg harbor 8-20 or 21-50 BPs of buzzards on average, with lower densities commonly occurring in the fringes of the state that partly belong to its territory. The higher density areas that were categorized as having 51-150 BPs occurred mostly in the southeastern districts of Spree-Neiße and Oberspreewald-Lausitz. For the purpose of our study, we particularly used the lower-class border of the available buzzard BP data in the state. Therefore, the lower-class border of the highest possible class of BP of buzzards available in the study area was 51 BPs. Following Torres et al. 2013, we calculated the strike susceptibility of buzzards at wind turbines by multiplying the assessed collision potential for the state of Brandenburg with the lower class borders of the BP of buzzards, signifying their relative density across the state using the Raster calculator function in ArcGIS version 10.1 (ESRI Inc., 2012).

Maximum Breeding Pair Density (BPD_{max}) = 51

Relative Breeding Pair Density (BPD_{rel}) = Observed Breeding Pair Density (BPD_{obs}) / Maximum Breeding Pair Density (BPD_{max})

$$BPD_{rel} = \frac{BPD_{obs}}{BPD_{max}} \qquad (1)$$

Strike Susceptibility (SC) = Collision Potential (CP) * Relative Buzzard Density (BPD_{rel}) * 100

$$SC = CP \times BPD_{rel} \times 100 \qquad (2)$$

The formula provides strike susceptibility for Buzzards at wind turbine structures that consider both, the density of Buzzards and the landscape influence on collision probability. Using the strike susceptibility potential, we made a spatial assessment of the number of existing wind turbines, number of approved wind turbines and number of proposed wind turbines within the assessed areas in the state (LUGV, 2014).

Predictor DELV (Acronym)	**Full Model**	**Simplified Model**
FW	11.7	12.5
S	10.3	11.2
SB	10.1	10.5
SW	10.0	11.1
RA	9.6	9.8
GAS	9.1	9.4
SS	8.7	8.9
B	8.1	9.1
FF	7.4	8.5
GF	7.3	8.8
W	4.2	
F	3.6	

Table V. 2: The relative contributions (%) of the (DELV) predictor variables for BRT full and simplified models. Developed with cross-validation on data from 332 sites and a tree complexity of 12 and 10 respectively. The full model was fitted with 12 predictors and least contributing 2 were removed and the simplified model was fit with the remaining 10 predictors; Chapter VIII: Annex: Figure A9 & A10.

[1]*Acronyms corresponding to the predictor variables are described in Table V. 1.*

Results

The performance measures of the BRT model showed that the full model using all 12 DELVs, with a tree complexity (*tc*) of 12 and a default bag fraction (bf) of 0.5, fitted 1100 trees (*nt*) at a learning rate (*lr*) of 0.005. After the initial full model development, we further simplified the model to reduce the model complexity by sequentially dropping the least important variable with a test drop of up to 2 DELVs (Elith et al. 2008). Between the full model and the simplified model, only 10 relatively highly influential DELVs were selected for the subsequent run of the algorithm (Table V. 2; Chapter VIII: Annex: Figure A10 & A11). Therefore, the simplified model at a tree complexity (*tc*) of 10 with the same default bag fraction (*bf*) of 0.5 fitted the ideally required number of trees (*nt*) of 1300 at a faster learning rate (*lr*) of 0.005. The performance of the simplified model was assessed and compared with the full model using the cross-validation running a random dataset using 30% of the occurrence points to test the model. Both models performed very well at predicting the outcomes within the training data set and resulted in satisfactory cross-validation deviance (Table V. 3).

Model	No. of Sites	No. of DELVs	Tree Complexity (*tc*)	Learning Rate (*lr*)	Number of Trees (*nt*)	Highest DELVs % Contribution	*CV dev (%)	AUC Validation (Sensitivity, 1-Specificity)
Full	331	12	12	0.005	1100	**FW (11.7)** **S (10.3)** **SB (10.1)** **SW (10.0)**	21(0.97)	0.86 (0.69, 0.02)
Simplified	331	10	10	0.005	1300	**FW (12.5)** **S (11.2)** **SW (11.1)** **SB (10.5)**	23(0.92)	0.88 (0.51, 0.01)

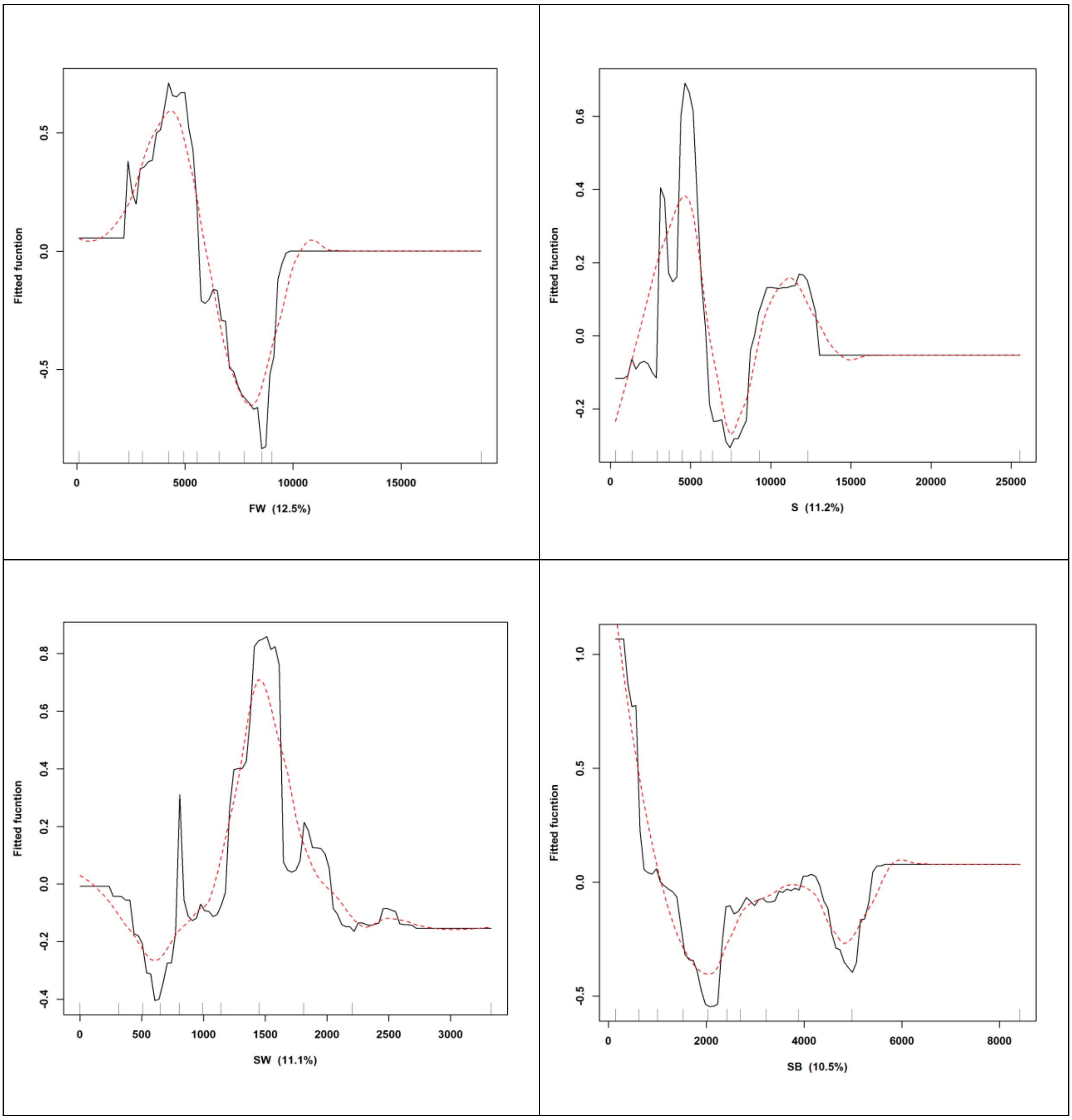
Table V. 3: Characteristics of the BRT Full and Simplified models and their predictive performance as evaluated on the test data, within a cross validation. Both models developed with cross-validation on training data, learning rate of 0.005, using variables listed in Table V. 2.

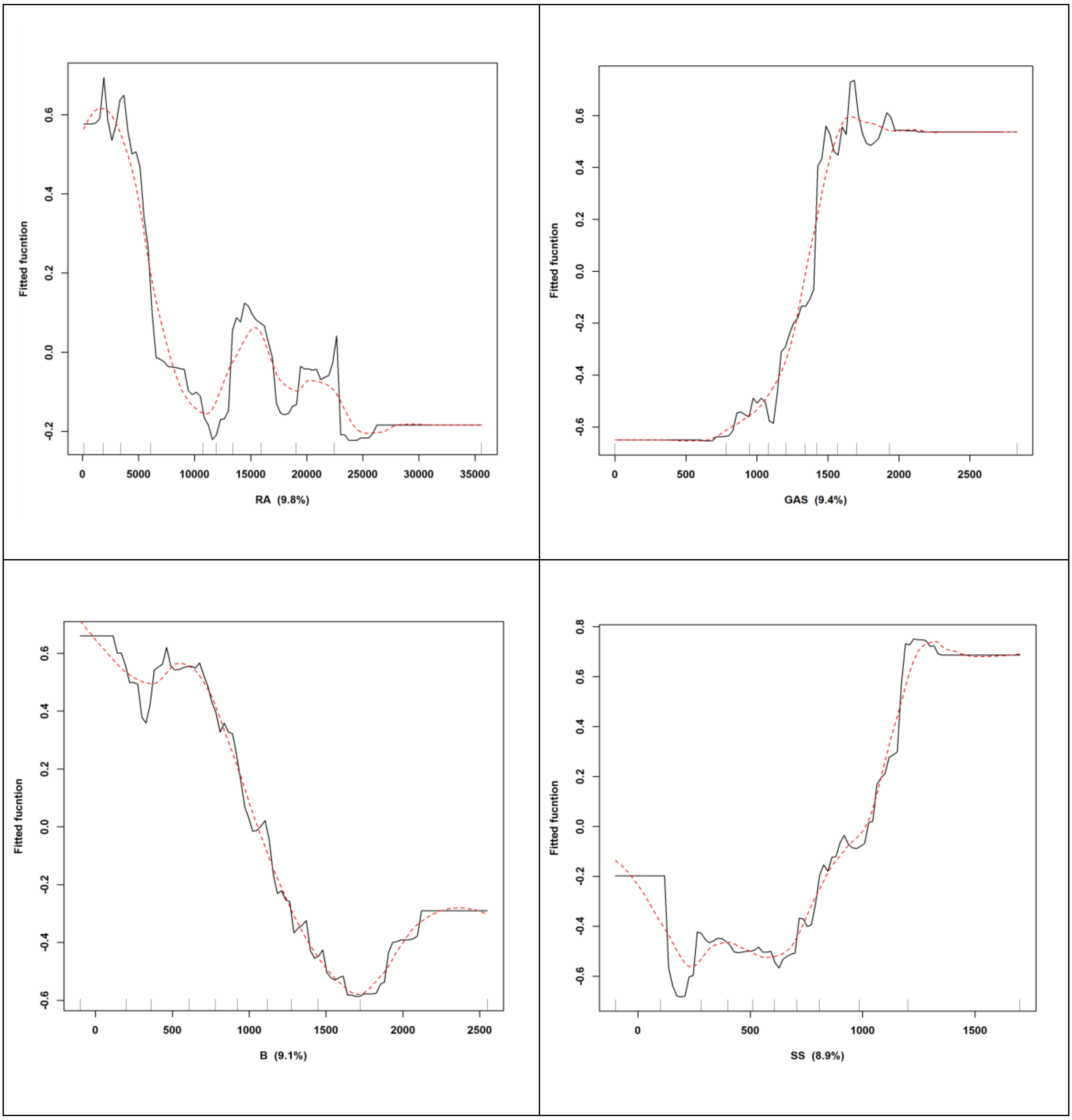
** Mean, with standard errors in brackets*

[1]*Acronyms corresponding to the predictor variables are described in Table V. 1.*

Although the validation test of the simplified model indicated a relatively low true positive rate (sensitivity = 0.51) compared to that of the full model (sensitivity = 0.69), both maintained low false-positive rates (1-specificity = 0.01 and 0.02, respectively); correspondingly, the overall discrimination of the simplified model (AUC = 0.88) was relatively equivalent to that of the full model (AUC= 0.86) (Table V. 3).

The highly influential predictor variables according to both models were the distances to the edges of the watercourses, shrublands and special recreational parks and biotas, which together accounted for approximately 45% of the total variance in the simplified model and approximately 40% of the total variance in the full model. Among the other predictors, the distances between 1-2 km to the edges of the green and open areas around settlements (mean contribution: approximately 9.2%) contributed highly to both models. The distances to the edges of the special recreational parks and biomes up to approximately 4 km had high contributions to both the models (mean contribution: approximately 10%), followed by the distances to the edges of bushlands up to 1 km, which also showed substantial contributions (mean: approximately 8.6%). The vicinities of the open grasslands and areas with forb communities (between 0 and 500 meters) also contributed to the higher collision potential revealed by both models (mean contribution: approximately 8.05%), whereas the distances to fields contributed the least (less than 3%) (Figure V. 2).


Fitted fucntion
FW (12.5%)
Fitted fucntion
S (11.2%)
Fitted fucntion
SW (11.1%)
Fitted fucntion
SB (10.5%)


Fitted fucntion
0.6
0.4
0.2
0.0
-0.2
0
5000
10000
15000
20000
25000
30000
35000
RA (9.8%)
Fitted fucntion
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
500
1000
1500
2000
2500
GAS (9.4%)
Fitted fucntion
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
500
1000
1500
2000
2500
B (9.1%)
Fitted fucntion
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
500
1000
1500
SS (8.9%)

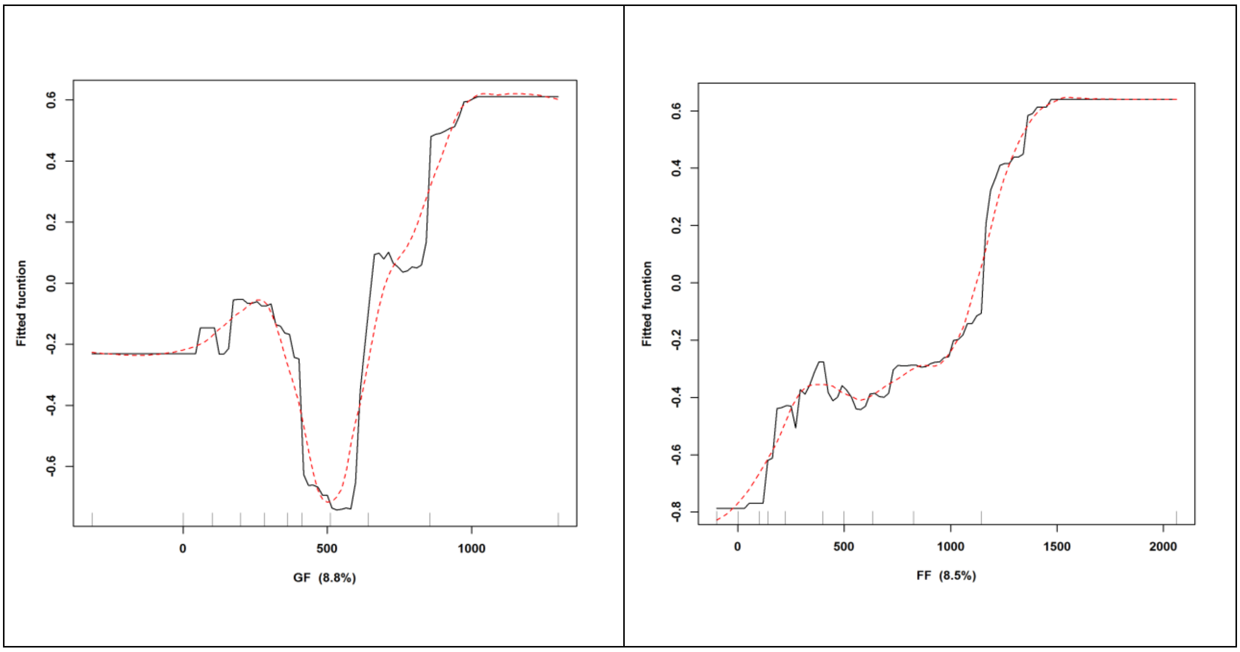


Figure V. 2: Fitted-functions produced by boosted regression trees of collision potentials for buzzards at wind turbine structures depicting the marginal effect of collision possibility (y-axes) by each DELV. Contribution of each DELV is given in brackets. Rug plots show distribution of the data across distances of particular DELV's in meters and are used as a measure of confidence across the shapes of the fitted-functions. Signs denoting (+) are distances outside the edge of the land use variables and (-) are distances inside the edge of the land use variables.

The extent of the pairwise interactions between the DELVs was also calculated; among all interactions, substantial pairwise interactions were found between the distances to the edges of the special recreational parks, biomes and settlements and the structures (variable interaction=0.58). In addition, the distances to the edges of the green areas around settlements also showed relatively higher interactions with the distances to the edges of flowing watercourses (variable interaction=0.53) and to the edges of the special recreational parks and biomes (variable interaction=0.51). The variable indices of these interactions were further used for plotting their interactions to analyze the combination of the distances between the specific pairs with the highest strike risks (Figure V. 3, Figure V. 4 & Figure V. 5).

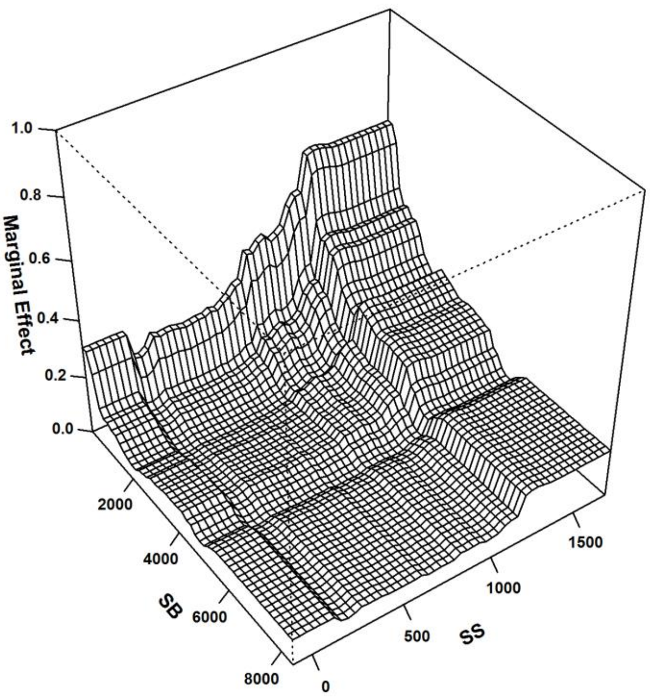


Figure V. 3: BRT 2-way: Interaction plot for distances to the edges of special biotas and the edges of settlements and structures; the most important interaction in the BRT 2-way model; interaction size= 0.58.

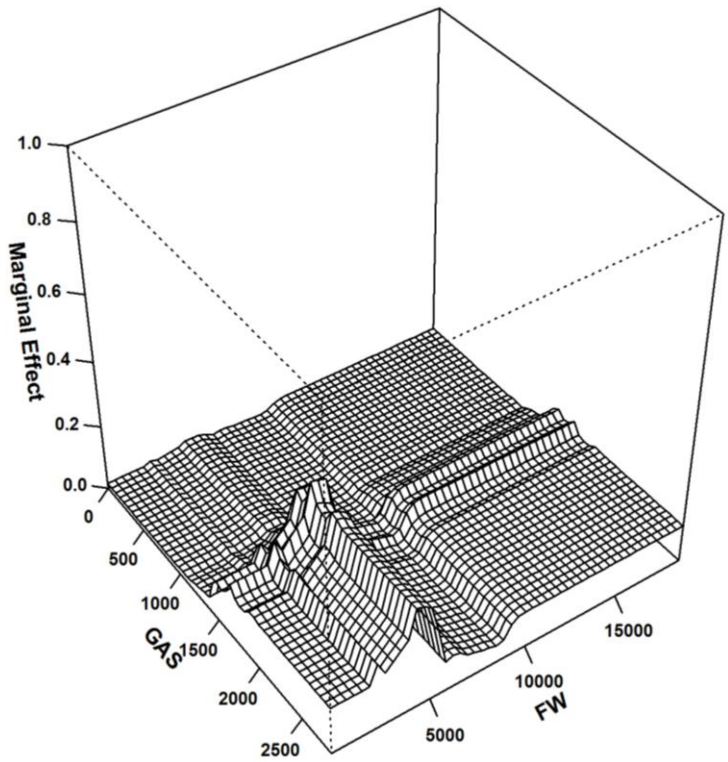


Figure V. 4: BRT 2-way: Interaction plot for distances to the edges of green areas around settlements and the edges of watercourses; the second most important interaction in the BRT 2-way model; interaction size= 0.53.

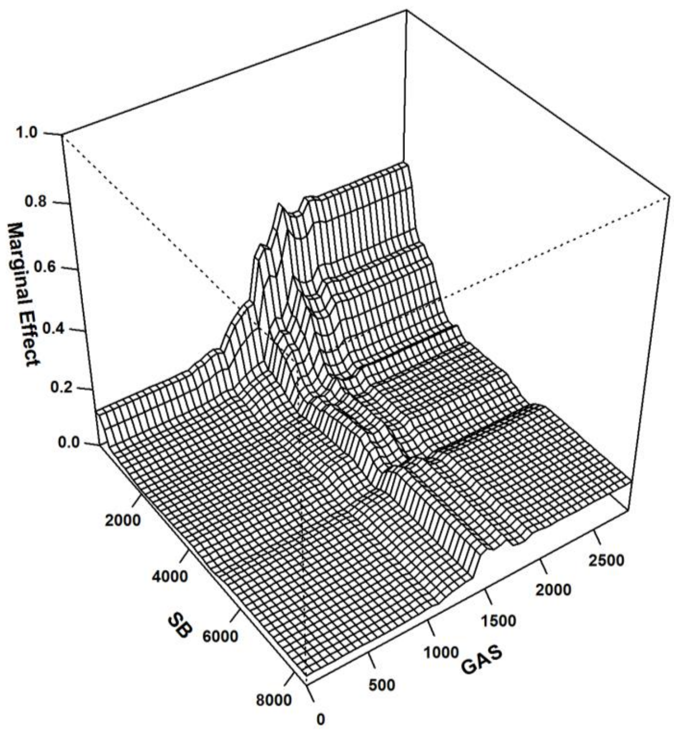


Figure V. 5: BRT 2-way: Interaction plot for distances to the edges of special biotas and the edges of green areas around settlement; the third most important interaction in the BRT 2-way model; interaction size= 0.51.

We also predicted the collision potentials for buzzards at the wind turbine structures to the DELV-based map of Brandenburg (Figure V. 6) using the predict function in the 'raster' package (version 2.0-12, Hijmans and Etten, 2012) of R (R Development Core Team, 2013) and spatially calculated the strike susceptibility using these predicted collision potentials and the density of buzzards in the region (Ryslavy et al. 2011) (Figure V. 7). Our analyses suggest that the majority of the habitats predicted to have higher collision potentials are less susceptible to strikes (Figure V. 8) and that the collision potentials face relatively higher strike susceptibility (> 60%) at only some locations. In parts of the districts of Oberspreewald-Lausitz, Uckermark and Havelland, the predicted higher collision potential areas overlapped with significant densities of buzzards (Ryslavy et al. 2011) (strike susceptibilities > 80%). Moreover, we can see that buzzard pair density was higher in NE, NW, South, and West of Berlin area (Figure V. 7) and in Figure V. 1, we can see that WTs are in dense clusters in NE, NW and West of Berlin area and more equally spaced in the South. We found that functional wind turbine density coincided with the density of collision events towards the NW of the state (Figure V. 9 and V. 10). Additionally, the spatial count of the number of approved and proposed wind turbines (Figure V. 11; LUGV, 2014) to be deployed in these highly susceptible zones were also detected, and found to be merely 0.29% (4 turbines) of the total (1343 turbines) in the planned phases of wind energy development projects (Table V. 4).

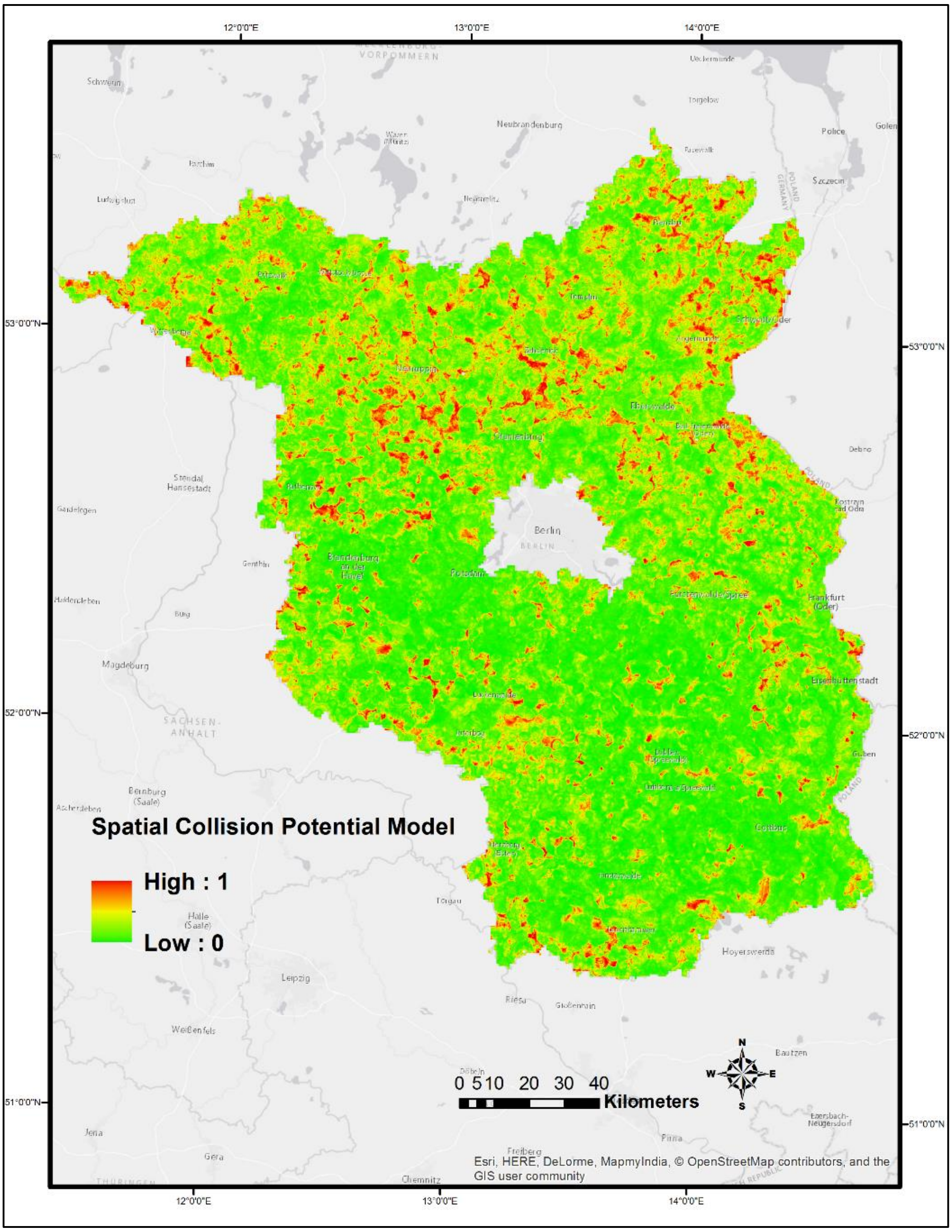


Figure V. 6: Spatial Collision Potential Model for Buzzards at WTs in the study region of Brandenburg, Germany

Approved Turbines	Buzzard strike susceptibility at WTs	No. of Turbines	%
	0% -20%	856	92.14
	21% - 40%	67	7.21
	41% - 60%	2	0.21
	61% - 80%	3	0.33
	81% -100%	1	0.10
Proposed Turbines	**Buzzard strike susceptibility at WTs**	**No. of Turbines**	**%**
	0% -20%	382	92.27
	21% - 40%	32	7.72
	41% - 60%	0	0
	61% - 80%	0	0
	81% -100%	0	0

Table V. 4: Turbines in the approved and proposed phases of development in the federal state of Brandenburg planned across the Buzzard strike susceptibility zones.

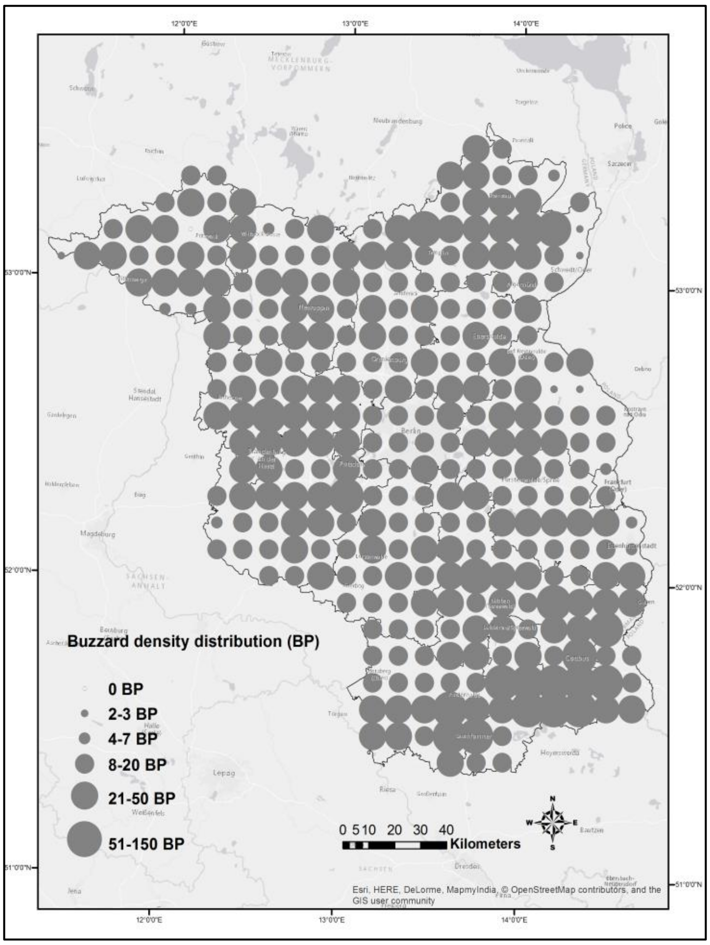


Figure V. 7: Regional densities of Buzzards in the study region of Brandenburg, Germany

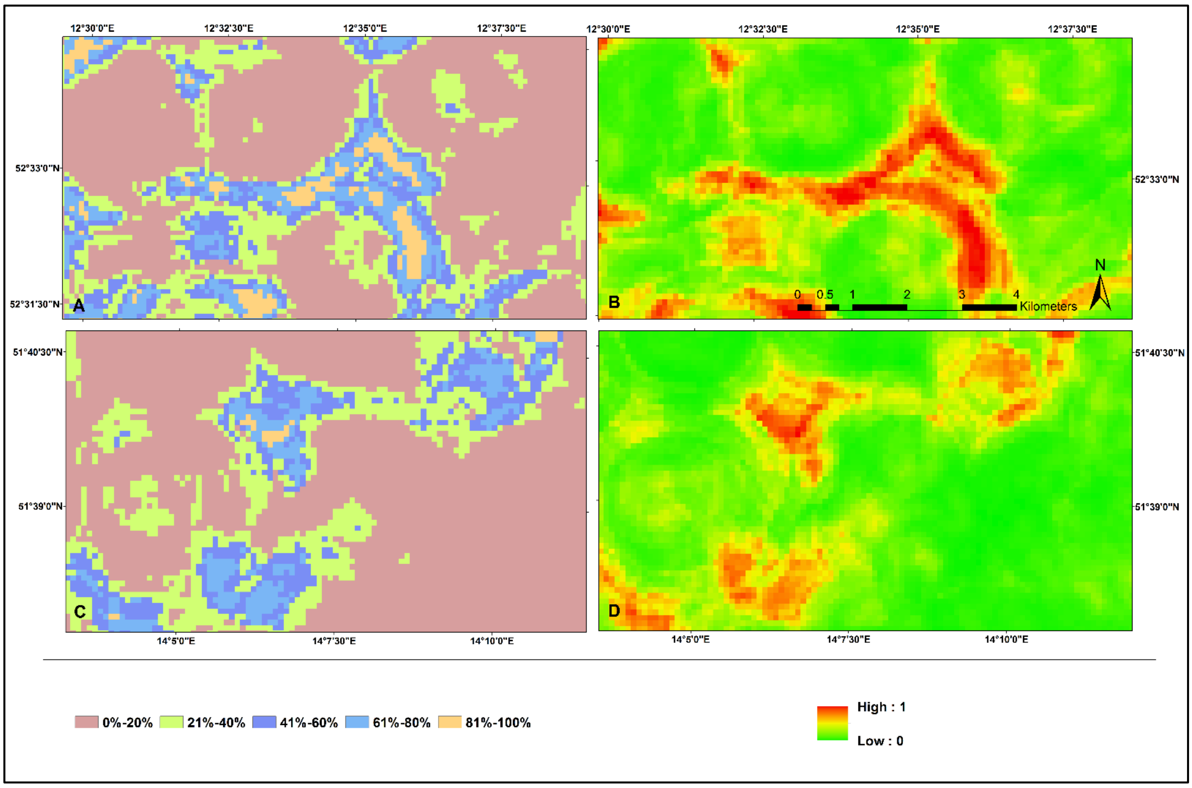


Figure V. 8: Strike susceptible locations for Buzzards at WTs in the study region of Brandenburg, Germany

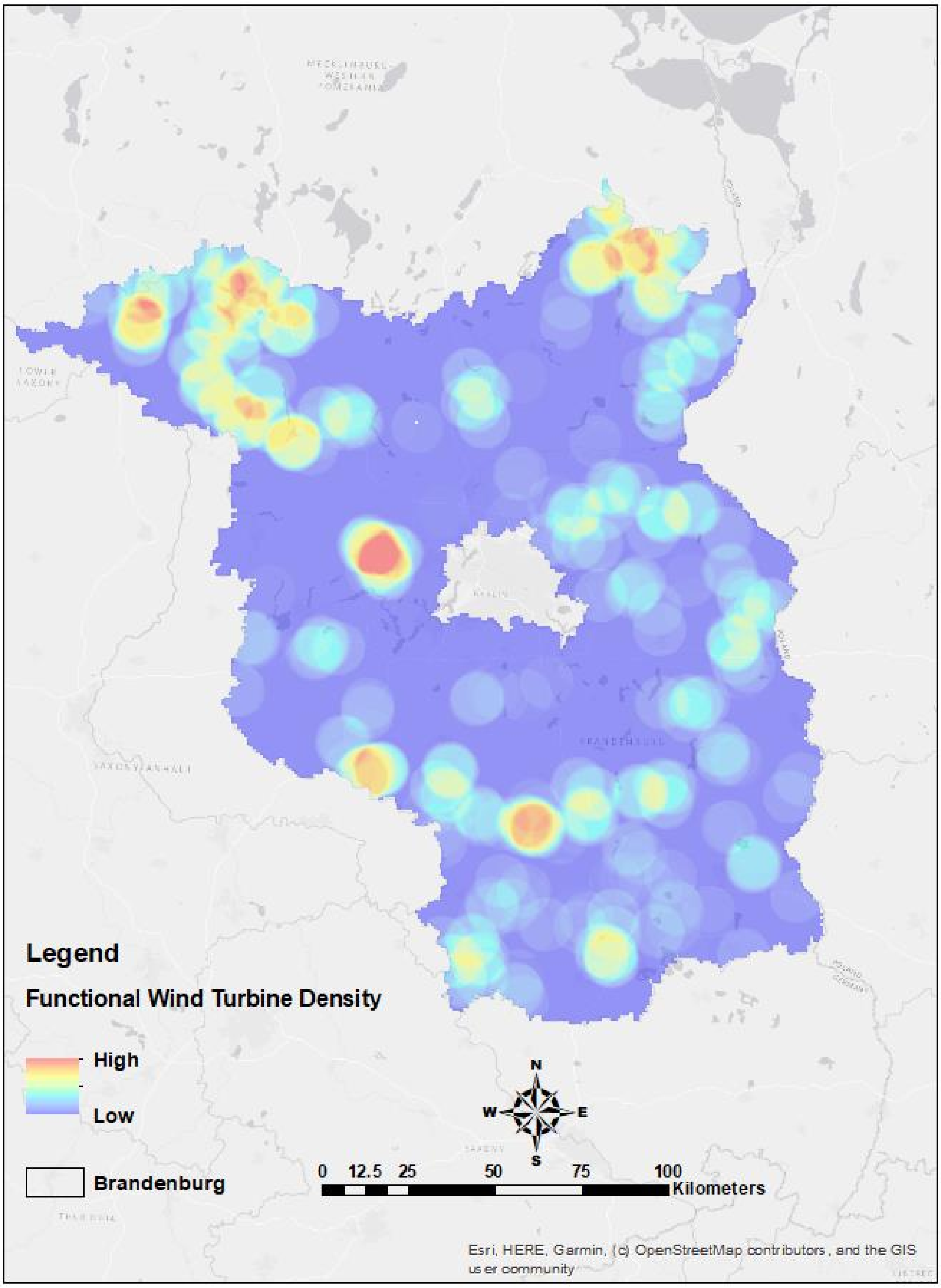


Figure V. 9: Functional wind turbine density in the study region of Brandenburg, Germany

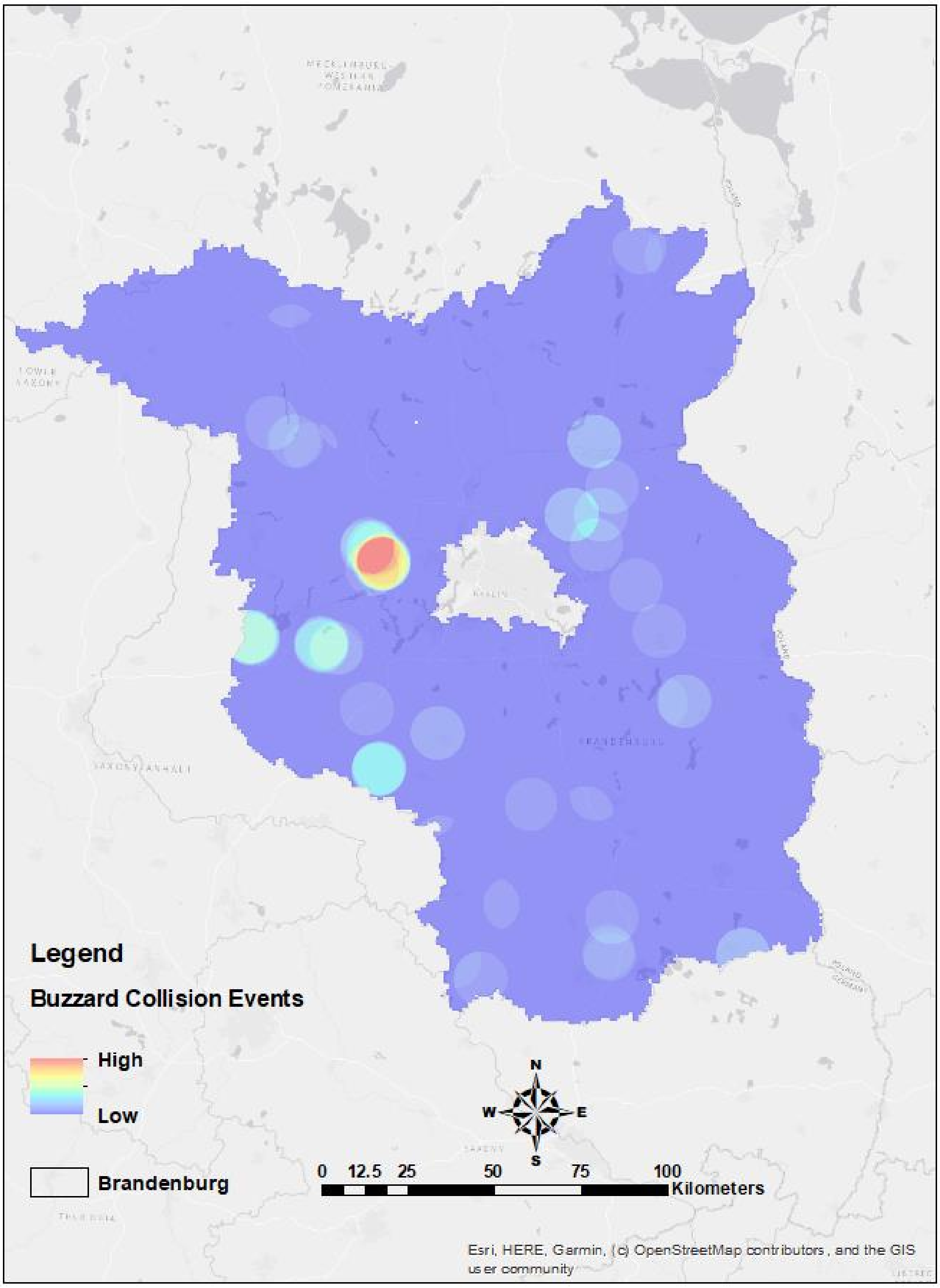


Figure V. 10: Buzzard collision events density in the study region of Brandenburg, Germany

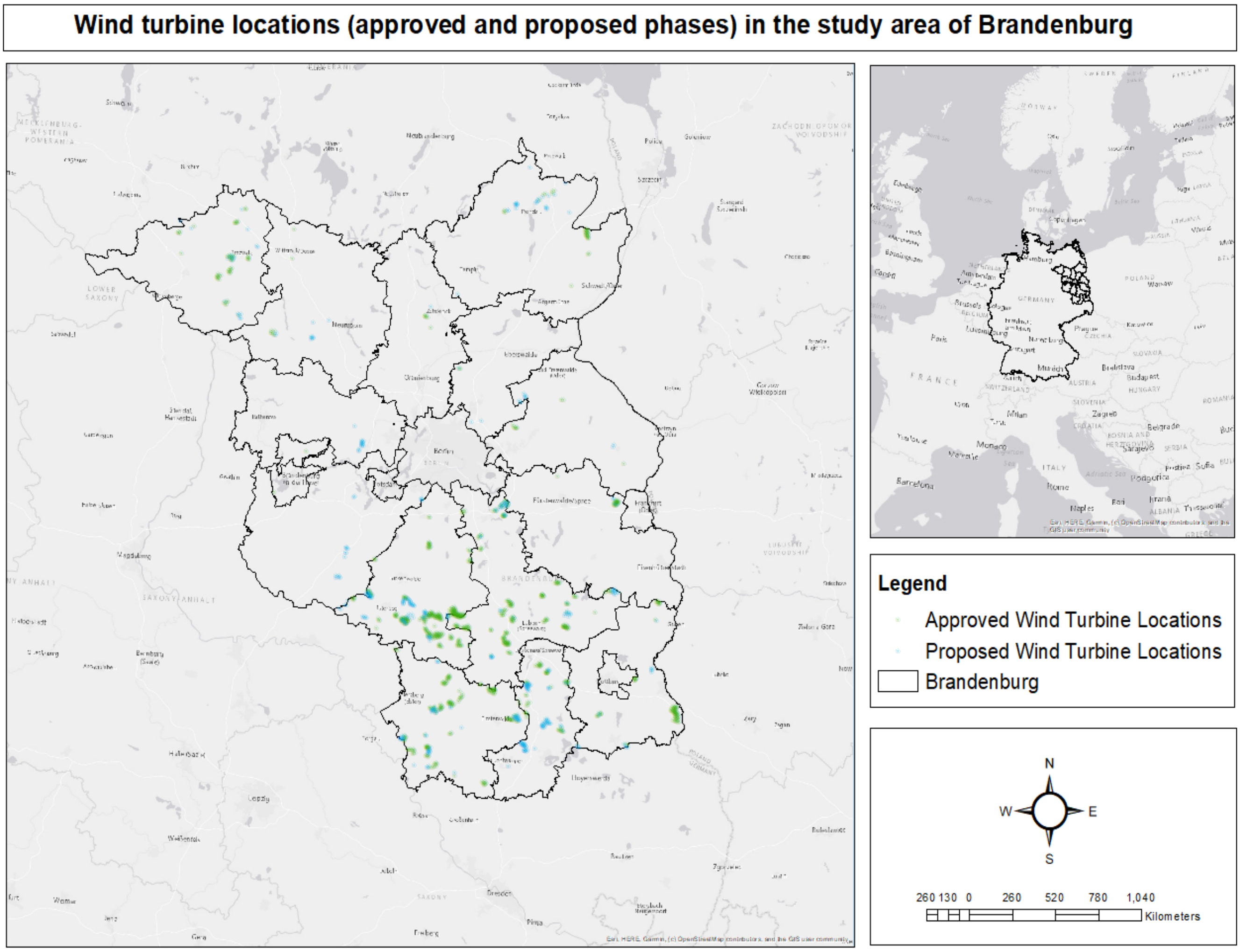


Figure V. 11: Spatial locations of the to-be deployed wind turbines in their approved and proposed phases of development in Brandenburg, Germany

Discussions

Previous studies based on systematic searches of collision carcasses of birds around wind turbine structures, have not only estimated the number of birds dying as a result, but also highlighted the seasonal changes between the detections (i.e., collisions in the first place itself). Numerous studies have analyzed the impacts of turbine- and the wind park overall- parameters with respect to the individual turbines (tower height, rotor radius, rotor swept area, color, light) even the habitat parameters with respect to the positions of the turbines in the wind park (land use, distance of woodlands or water bodies to the mast foot of the turbine) and finally evaluated the accuracy of collision predictions of birds by assessing the success of future detections at the predicted locations (Grünkorn et al. 2009; Dürr, 2011; Illner, 2012; Eichhorn et al. 2012; Bellebaum et al. 2013; Hötker et al. 2013; Rasran and Thomsen, 2013; Rasran and Dürr, 2013; Schreiber, 2014; Langgemach and Dürr, 2015; Weitekamp et al. 2015; Grünkorn et al. 2016)

On similar lines, by means of our study; we also aimed to better understand such collision distribution patterns of birds in relation to the placements of individual turbines along the various habitat use patterns around different land use types. Our endeavor was to develop conflict reduction strategies via medium of avoidance distances to direct collisions for wide-ranging species. We used this powerful tool of boosted regression trees (BRTs), which is a combinational algorithm based on statistical and machine-learning techniques, for giving general guidelines on wind power plant planning in relation to the most important landuse type variables for birds, by producing a spatially explicit map predicting their collision risk across the landscape on turbine installations. We limited the scope of our study only to that of the common buzzard (*Buteo buteo*) to predict the exposure of the collision risks to buzzards at wind energy structures. Careful site selection is crucial to reduce the risk of collision, especially in species such as the buzzard which does not seem to actively avoid wind turbine.

Our study predicted the spatial patterns of wind turbine collision risks to buzzards by assessing relationships between the actual spatial occurrence of collision fatalities and bird behaviors in terms of proximities or distant preferences to different habitat features of multiple landuse types. By using the long-term carcass search data of buzzards detected around turbines; in relation to the distances of these turbines to the different land use types, we developed a spatially explicit collision distribution model for the species across the state. Additionally, the assessed collision risk areas were further compared to the regional densities of buzzards to generate their actual strike susceptibility on turbine installations across the region.

Before discussing our findings, we would like to emphasize again that our study does not rely on systematically collected, spatiotemporally homogenous bird collision data from the wind turbine structures, but on opportunistic data collected. Therefore, although our records cover a wide area, we do not know if the search regime was comparable across the study region and collected with uniform search efforts and comparable search protocols. These limitations biased the results in terms of the probability of the A.) carcass persistence times due to scavenger and predator activities and B.) the detection inadequacies of the researcher, with varying efficiencies across different substrates and species of birds involved (Erickson et al. 2014). Resulting in lack of true pseudo-absence data, which in turn led to weak and partial inferences from the predictor variables. These limitations were not unique to our study; species modelling procedures involving home range estimations, distribution evaluations and movement assessments face similar challenges regarding data issues (Kéry et al. 2010; Hull and Muir, 2010; Lahoz-Monfort et al. 2014; Guillera-Arroita et al. 2017). These limitations should be kept in mind when interpreting the results of our study. Yet, we rule out that the carcass search operations data was biased towards wind turbines, because the all the dead bird carcasses were reported to the regional authorities and not just wind turbine collision fatalities.

Analyzing the spatial information alone, we found that the density of collision events was higher in areas with higher densities of wind turbines, this effect was predominant in areas with higher regional population densities particularly (Figure V. 7, V. 9 and V. 10). This implies that collisions are correlated with WT density, synonymous with studies showing wind turbine densities as strong predictors of collisions, affirming the synergistic effects of wind turbine density by amplifying collision events (Schaub, 2012), especially in areas with high buzzard density. Therefore, WT density is a critical predictor of collision, and it would have great implications on the collision risks in dense population areas. Moreover, combining collision events densities and regional species densities allowed for better predictions of collision risks (Figure V. 8).

These results indicate that considering a combination of data on wind turbine densities along with collision events and regional population densities allows for improved assessments of collision distribution and strike susceptibilities at large spatial scales for wide-ranging birds, such as such large raptors. Therefore, our results support and encourage the use of models that use combinational data as a tool for the analysis of collision potential on larger spatial scales, as has been already done for many other bird species (de Lucas et al. 2012; Reid et al. 2015; Vasilakis et al. 2016; 2017).

However, the authors would like to clearly and understandably state that despite the usefulness of their study for regional planning processes, our collision distribution and strike susceptibility models are neither a substitute for detailed population monitoring nor for site-specific Environmental Impact Assessments (EIAs) in the course of project planning. While interpreting the results of our study it is highly necessary to adjust our recommendations made for buzzards according to the specific situations present in different study regions.

The recent shift in focus regarding the deleterious effects of wind turbines from red kites to buzzards, despite the equivalent number of collisions at WTs over the years, buzzards were not considered in the planning criteria earlier (Grünkorn et al. 2016) because their widespread population makes them seven times as common as red kites in Germany (Bauer et al. 2002). Prohibitions to planning wind turbines with regard to species protection mostly consider species facing detrimental influences at their local population levels and exclude species that are common and widespread; collision-based losses are not considered a serious conservation issue for these species, e.g., the common buzzard (Stadt Rheinbach, 2015). However, currently in the state of Brandenburg, the inclusion of the buzzard-only criteria in the spatial planning of the turbine locations is also becoming increasingly important due to the consequential forecasted decline in the population of the species (Grünkorn et al. 2016, Weinhold, 2016). Moreover, as the species is also known to occur almost everywhere in the state, selecting the lowest risk options for turbine deployment is the only strategically sound method for the continued expansion of wind power in the state.

Buzzards in general, have not shown any appreciable changes across their distribution range in Brandenburg compared to their estimated range since the mid-1990s (ABBO, 2001), they have also not indicated avoidance behaviors with regard to wind energy structures (Bergen, 2001). They often approach the wind park within a few meters and use the transformers or the railings of the stairs as raised hides, making courtship flights and rare hunting flights at the hub height or above the rotors (Sinnig and Gerjets, 1999). Apart from the target species, the future of wind power expansion in the state may also be unlikely, i.e. any striking changes to its spatial plan due to the innumerable number of deciding factors influencing the locations of wind turbines. As expected, the deployment of new wind turbines in most cases would either be near the vicinity of the existing turbines, adding to the output of a pre-existing wind farm, or be replaced with repowering the old wind turbines (LUGV, 2014). In addition to this, as our study region is in the North Eastern Germany, that has not experienced any strong land conversions over the recent decades (Kuemmerle et al. 2016), we can assume that our analyses based on the landuse type variable against the placement of turbines should not bias our results.

Buzzards are also area-sensitive species that occupy almost all habitats in the cultural landscape as long as there are suitable tree populations or artificial heights that function as breeding and nesting locations, as they prefer the use of several kinds of synonymous high natural and artificial perches (Glutz et al. 1989; Hubert 1993; Penteriani and Faivre, 1997; Mülner, 2000; Probst 2002), commonly at the edges of forests (Hubert 1993; Hohmann 1994; Graham et al. 1995). This preference has been attributed to the ease of access to the nests and to a need of unobstructed view of the surrounding landscape (Hubert 1993). Therefore, maintaining a minimum distance to the fringes of the forested areas, woods surrounded by fields, tree groups and individual trees in bushlands and special recreational parks and biomes is an important planning consideration for the location of wind turbines to avoid possible collisions. Carcasses have been detected near wind turbines situated up to 750 m and 2000 m from the edges of these land use types (Figure V. 2).

In addition, preventative measures, to the degree that they are possible through design and effective area usage, are also recommend for the deployment of wind turbines in areas with prey attraction in the direct vicinity of the planned locations. This could include avoiding fallow lands, green and open grasslands or shrublands near the locations, as the amount of grassland and the amount of dry land are parameters strongly related to vole-hole density (Schindler et al. 2012). Although a direct connection to agricultural use does seem to exist as hunting buzzards frequently prefer fields without vegetation; it can be assumed that higher vegetation limits food visibility in an area, and thus lower and less vegetation is more favorable for food acquisition (Penteriani and Faivre, 1997; Bergen, 2001). Suggesting, it is essential to avoid the unintentional creation of attractive food habitats at the mast foot of the turbines due to the construction of small paved paths to access the turbines. The creation of such open areas, which have a higher edge density of greater accessibility to the potential prey base (e.g., small mammals), is widely known to increase the collision risk for the species. Additional affinities to open areas are also attributed to the promotion of courtship behavior (Cerasoli and Penteriani, 1996; Penteriani and Faivre, 1997).

Apart from agricultural fields, buzzard collisions also showed no affinities towards distances from watercourses. Buzzards do not select nest sites near open waters; neither the distance to the path of the watercourses influence the buzzard nest-site selection (Hubert, 1993). The carcasses detected at the wind turbines were situated farther than 2500 m from the borders of the flowing watercourses but closer in comparison from the borders of still watercourses: between 300 m and 1750 m (Figure V. 2).

The carcasses detected at the wind turbines primarily situated at distances closer to the edges of green and open areas around settlements (Figure V. 2), recommend that wind turbine planning should include a free approach and departure-based technique in such areas. With distances particularly between 750 m and 1750 m from the borders of green areas around settlements to be specifically avoided, i.e. avoidance of raised areas adjoining areas with open landscapes serving as possible hunting grounds, which would ultimately reduce collision risks in these areas, especially during breeding, because buzzards prefer the vicinity of their feeding areas to be in close proximity to their nesting hides (Newton, 1990; Kenward et al. 2001a; 2001b).

The solutions in all cases, primarily require additional efforts in collection of the resource data. We recommend, a standardized monitoring protocol to be developed and applied prior to installations to each wind turbine construction site on a monthly basis and for a time of at least three years. Furthermore, the data from the Environmental Impact Assessment studies should be made freely accessible for monitoring on regional (state) and nationwide monitoring and research. However, post installations, there is usually relatively high-quality data for birds of prey (Grünkorn et al. 2009; Bose et al. 2018) despite the afore mentioned limitations due to the greater persistence times and the efficiencies of detection of their carcasses (Erickson et al. 2014). Therefore, for successful predictions and adaption of planning directives in this field, Population Viability Analyses are highly recommended (Grünkorn et al. 2009). In our study, the involved spatiotemporal variation was already high, which pertained to the limitations of the subsequently higher costs of data collection associated with labor requirements, further adding to the limitations. Analyses like the one we did can support the spatial planning process on regional and federal scale if not also on national scale by identification of areas with a lower risk for collision with the mentioned species. However, more research and assessment must be done with different species as well e.g. application of joint SDMs etc. These findings are particularly relevant for planners and policy makers. The differential response of birds reported suggests that it is possible to locate wind farms and to plan changes in land use in accordance with conservation interests. Depending on regional conservation priorities, it may be possible to locate suitable wind turbine sites that might affect species of lower conservation concern or even benefit those in need of conservation action. Furthermore, consideration must be given to the ecological role of these species from a wider ecological perspective.

Although we expect our approach to be applicable at the turbine deployment sites of the given study region this methodology is applicable only for a case-by-case review, taking into account the different land use types, their included features, the nearest distances to these features and the detailed information regarding the target species. Since the study predominantly focuses on buzzards and only on “direct” collisions with the wind turbine structures, it captures only one of the many ecological impacts of wind energy infrastructures. Therefore, the authors would like to clearly and understandably state that this study cannot be a substitute for an ecological impact studies at wind energy development projects. It is necessary to adjust our recommendations made for buzzards according to the specific situations present in different study regions for different species in question. Nevertheless, the best approach is not to expect the models to be an ultimate endpoint but instead to follow it as a guide for consultation within limited resources and should not be used as a sole decision-making tool for the selection of suitable wind turbine sites.

Chapter VI: Synthesis

With avian collisions at wind turbine structures rapidly developing as a cause of serious conservation concern threatening multiple bird populations, the study aimed at assessing the collision risk areas for birds in the landscape prior to wind turbine installations by ascertaining the conditions pertaining at the wind turbine locations with detected collisions; exclusively their sensitive distances to different land-use types. These combinations of distances the different land-use types that promoted the collision phenomena, enabled the accurate guidance of future wind farm expansions in the landscape avoiding the assessed collision risk areas and advising post-construction fatality search operations around turbines that are already installed in these areas.

The study makes a relevant contribution towards the identification of these collision risk areas by employing approaches of species distribution modelling (SDMs). The carcass survey-based collision data when used as a proxy for species presence against the landscape-based variables enabled the prediction of risks areas of bird collisions at wind turbine structures prior to installations. This approach allows identification of the distances to different land-use types that in combination elevate the risks of collisions and thus determining wherever such combinations of distances existing in the landscape, that might be prone to collisions.

The core contribution of the project was to aim for the spatial allocation of wind turbines in the landscape avoiding bird collisions. Three central research questions formed the core of this thesis:

1. Using the ordination procedure of Ecological Niche Factor Analysis (ENFA) to assess the collision niche profiles of the frequently-hit bird-groups as per the carcass search surveys around wind turbine structures in the federal state of Brandenburg, Germany.
2. Investigate the utility of Random Forests (RF) for the predictive modelling of the possible spatial distribution of bird collision risks based on the different collision probability thresholds at the wind turbine structures in the federal state of Brandenburg, Germany.
3. Examine the strike susceptibility and the collision patterns of the Common Buzzards (*Buteo buteo*), using the ensemble method of boosted regression trees (BRTs). Perform an intersection between their assessed spatial collision risks and their regional densities to assess avenues of possible spatial segregation.

These assessments proved to be powerful tools for landscape planning, especially in the identification of sets of sensitive distances to different land-use types and highlighting areas that confer higher risks of avian collisions on turbine installations, that can be ultimately translated into allocation strategies for wind turbines in the future.

Each of the research questions have been outlined in Chapter II and covered in Chapters III-V and are next reviewed together.

6.1 Preface

The current practices in the planning processes prior to siting of wind farms, (particularly in the case of the federal state of Brandenburg in Germany) follows the basic principle of mitigating the impacts on bird species by maintaining a sufficient recommended distance between the wind turbines and their respective breeding sites and/or roosting sites and also to the core areas with higher congregations of birds (Isselbächer and Isselbächer, 2001; LAG VSW 2015). These distances are used as first approximation, within which an increased flight activity i.e. collision prone behavior can be expected (Isselbächer and Isselbächer, 2001; Hötker et al. 2013; LAG VSW 2015). The greatest impediment of this practice is the suitability of the recommended distances to avoid, only during the breeding season - as the breeding sites are activity centers mostly during that time of the year (Grünkorn et al. 2017). However, with fatalities also observed round the year, i.e. outside the breeding seasons (Dürr et al. 2015), and with activities of species unevenly distributed across different habitats and also in the same habitat over the years (Grünkorn et al. 2017), many studies have confirmed non-linear relationship between the pre-construction bird abundance monitoring and post-construction detected collision at given development zones (De Lucas et al. 2008; Ferrer et al. 2012). Therefore, the effectiveness of these recommended minimum distances remains uncertain (Grünkorn et al. 2017; Bose et al. 2018; 2019; 2020).

As collision rates differ among wind farms and also among wind turbines within the same wind farm, the occurrence of fatalities should logically be related to specific range of different environmental variables associated with the particular location of the affected wind turbine within the wind farm. Specifically, to the distances between the affected and the non-affected turbines within the farm, and more importantly to their actual positioning in the landscape i.e. distances to different land-use types (Bose et al. 2018).

Therefore, for the purposes of the study I chose to focus on distances of the turbines to different land-use types as the environmental variables influencing collisions. I particularly highlighted distances to landscape features (belonging to their respective land-use types) around the locations of the WTs, because distances are often required when policymakers ask for information, to ensure the safe deployment of WTs in the landscape. The determination of the increase and decrease of collision risk at distances in the immediate vicinity or distant away from specific landscape features can therefore help proposing safer placements of WTs in the landscape and identify areas where the risks of bird collisions could be minimized in advance. Moreover, with continuous advancements in turbine specifications (related to rotor blade lengths, turbine tower heights etc.) to generate more and more energy, along with no possible control on meteorological conditions or ornithological behavior that together govern bird collisions at wind turbines, this is the best step forward, to focus on delineating ecologically sensitive distances for taxa towards habitat elements and avoiding these distances for turbine installations (Bose et al. 2018; 2019; 2020).

The study makes a relevant contribution towards the identification of collision sensitive distances to different land-use types, to therefore highlight areas that confer higher risks of collisions on turbine installations by employing approaches of species distribution modelling (SDMs). The approach also identifies the sets of combinational distances to different land-use types that elevate the chances of collisions, classifying wherever such combinations exists in the landscape to be prone to collisions.

The study based on carcass detection studies, was limited by constraints of spatiotemporal inconsistencies in the dataset. Enhancing this problem of bias, was also the unavailability of information pertaining to the boundary conditions of the detected carcass dataset. In the case of this study, the underlying material is an opportunistic set of data collected from unsystematic surveys of different intensities and durations, along with inclusions from accidentally found and otherwise reported carcasses in the dataset under investigation as well. (Bose et al. 2018; 2019; 2020).

Therefore, I used a conservative approach of the detection and non-detection to assess the combination of predictors that created an increased risk of bird collisions on turbine installations. I solely utilized the respective spatial information of the turbines with detected carcasses and the ones without any detected carcasses, neglecting the detailed but often very biased associated information; 1. regarding the estimated numbers of birds discovered in each detection, 2. differences in carcass search monitoring efforts, ranging from only one time controlled turbines to many frequently and regularly controlled turbines across all the windfarms in the study area (Bose et al. 2018).

6.2 Conclusions

Using the abilities of Ecological Niche and Species Distribution Modeling, the study and was able to particularly: predict the high collision risk areas in the landscape of Brandenburg, Germany for the frequently-hit bird-groups; i.e. raptors, pigeons, larks, crows and buntings at wind turbine structures (Bose et al. 2018; 2019; 2020), and assess the range of sensitive distances to the different land-use types that could promote the collision phenomenon, i.e. the ecologically important distances between and within multiple land-use types to the affected wind turbines, in order to predict the collision response for the frequently-hit bird-groups (Bose et al. 2018; 2019; 2020).

1. In Chapter III, by means of Ecological Niche Factor Analysis the collision sensitive ecological niche of the worst hit groups of birds; Buntings, Crows, Larks, Pigeons, and Raptors was delineated. The main intent behind the examination was to assess to which particular land-use types and at what distances to these land-use types do WTs promote or reduce the collision risk, proposing approximately safer placements of WTs in the landscape and identifying respective collision niche overlaps and differentiations among the groups. The assessed collision niche for each of the groups depicted strong relationships between the turbines where carcasses have been detected and the following key land-use types: fields and other arable lands, forests and forestry areas, green and open areas outside human settlements and grassland and forb areas. It was noteworthy that the proximity of the detections (group-wise) to particular land-use types on which the collision sensitive niche analyses (group-wise) were based, were alike (Bose et al. 2018).

   Our results indicated that the distances to the edges of the flowing watercourses (distances farther than 2500 meters) as the most important indicator of collision in the case of Raptors, given their detours around large bodies of water. Furthermore, distances to settlements and structures and distances to the green and open areas around these structures (within 1 km) were also found to be of prime importance for Raptors & Crows given their respective affinities for the urban environments. Pigeons, on the other hand showed collision sensitivity to distances to the edges of forests and forestry areas especially around urbanizations (distances closer than 1 km), adapting their nesting requirements and foraging habits to be conducive to urban lifestyles. Likewise, the distances to the edges of shrub-lands (at approximately 2,500 meters distances) and the distances to the edges of grasslands (between 250-750 meters) were the major determinants in case of the classification processes for the Buntings and for the Larks, being shrub-land and grassland specialists respectively (Bose et al. 2018; 2020).

2. The relatability and differences between the collision niches of the different bird-groups were also assessed to indicate similar sensitivities, or niche differentiations indicating the reverse. In advent of overlaps between their respective niches, the study intended to propose the easily detectable species to serve as suitable proxies for birds in general for purposes of impact assessments of wind turbines. Using the simplistic ordination procedure of ENFA and LDA analyses, it was found that individuals of the worst hit group of birds in the state of Brandenburg showed an appreciable extent of overlaps between their collision spaces (Bose et al. 2018).

   The least observed niche overlaps based on turbine sites where collisions were detected show that the rather restrictive collision niche of Buntings has an insignificant overlap with the collision niches of other bird-groups, especially Crows. Crows being generalist omnivores (Marzluff and Neatherlin, 2006) and Buntings being shrub-land specialists (Rudnicky and Hunter, 1993; Rodewald and Vitz 2005, mostly show niche differentiations on grounds of their specific preferences towards proximity to green and open areas in and around settlements and proximity to shrub-lands respectively. This is in accordance with our pairwise discriminant analysis, showing turbines with Bunting and Crow detections having fundamental niche separations related to the distances to the edges of shrub-lands (favoring Bunting detections) and green areas around human settlements (favoring Crow detections). These results are also consistent with ENFA, where Buntings show higher global specialization values as compared to other groups (Bose et al. 2018).

3. Raptors on the contrary, showed greater overlap with all the bird-groups, most likely due to their greater home ranges as compared to many other birds of smaller size (Rodríguez-Estrella et al. 1998; Tanferna et al. 2013), venturing across distances to utilize perch and prey availability (Chace and Walsh, 2006). Indicating that the Raptor overlap is either an effect of the comparably larger parameter space covered by the Raptors or a better coverage of their detections in the study area because of their bigger sample size (Bose et al. 2018; 2020), i.e. the exceptionally high number of Raptor carcasses detected at WTs in comparison to other smaller birds, primarily due to higher searcher efficiencies in combination with longer carcass persistence times (Erickson et al. 2014). Overlaps between the respective collision niches of the bird-groups basically indicated similar sensitivities of birds to the multiple land-use combinations. Normally niche overlap is often used to indicate potential for competition between species Costantini, 2009; Sattler et al. 2013; Jung and Czetwertynski 2013) highlighting overlapping resource use e.g. the habitat niche overlaps between related species infer the potential for competition based on niche partitioning between the species.

   But in the study, as a contrast I used it with the intent to highlight, particularly their similar sensitivities to distances from land-use types. Their similar or disparate sensitivities to distances from different land-use types allows directing safer turbine positioning for protecting multiple bird-groups at once or for targeting a specific bird-group with limited overlaps with any other bird-groups. Raptors are also already known to play a very important role as flagship and umbrella species within general nature conservation strategies, besides being critical ecosystem services providers themselves (Donázar et al. 2016). Raptors might also be used as indicators and/or umbrella species useful for evaluating and managing mitigation measures (Moleón et al. 2007; Pérez-García et al. 2011; 2016) in a rather prospectively changing ecosystem and landscape due to human interests i.e. planning new infrastructures for wind energy harness (Donázar et al. 2016, Bose et al. 2018; 2020) in order to minimize any undesirable effects. Therefore, regional models for conservation planning based on such umbrella species may benefit many other nontarget taxa as well.

The study in Chapter III was solely based on the spatial location of the detected carcasses, giving a detailed descriptive analysis of the turbines with collisions with respect to their placement distances in the landscape. But, because the method was not suitable enough for predictions, this built the objective for Chapter IV complementing the ascertained knowledge so far. The methodological core of Chapter IV was employed to bridge the predictive shortcomings of the approach utilized in Chapter III. As SDMs focus only on the actual distribution rather than niche estimation in Chapter III. Like other uses, such as estimating invasive potential or assessing effects of environmental change on species distributional potential could be explicitly estimated via ENFA i.e. denoting potential distributions. SDMs could estimate actual distributions, when performed using Random Forests (Bose et al. 2020), a machine learning algorithm with wide prominence in the fields of nature conservation and environmental sciences; , such as climate change (Gaal et al. 2012), ecology (Cutler et al. 2007; Evans et al. 2011), forestry (Falkowski et al. 2009) and environmental remote sensing (Rodriguez-Galiano et al. 2011; Adelabu et al. 2014). In the study, the approach used the available binary strike response data from each of the frequently-hit bird-groups, allowing the identification of areas with different collision potential thresholds on construction of a WT.

4. In contrast from the study in Chapter III, the study in Chapter IV supported the further segregation of the collision risk areas under different probability thresholds of collisions, to only classify the areas with “exceptionally” lower collision probability thresholds to be interpreted as the actual “no risk areas”. The areas classified with lower collision probabilities could always lead to some non-negligible numbers of collisions. Amongst these areas, only the ones with “exceptionally” lower collision probabilities can be interpreted as free from collision risks and classified under the actual “no risk areas”. All other probability thresholds do have some risk or at least a residual risk of collision (Bose et al. 2020). Although the predicted areas with potential collision risks for the frequently-hit bird-groups; i.e. raptors, pigeons, larks, crows and buntings, in total had a small but highly dispersed expanse of approximately 2,130 km^2 across the vast 29,479 km^2 area of the federal state of Brandenburg, Germany (Bose et al. 2020). These results only when further segregated to assess areas based on their different

probabilities of collision thresholds (between 0 and 1), showed that the areas with probabilities of collision (with threshold; cut-off value >0.5) also had a small expanse across the federal state, especially in the cases of crows, buntings and larks. The raptors again showed the broadest coverage across the total collision space for this threshold; with approximately 3,054 km^2 (~10 %) and were followed by pigeons; with 945 km^2 (~3 %).

However, for the further probabilities (with threshold; cut-off value <0.5) the collision risks assessed in the region were relatively much lower for all the bird-groups, out of these areas, only the areas (with threshold; cut-off values <0.05) could be categorized as areas with significantly lower probabilities of collision, i.e., with raptors, pigeons, larks, crows and buntings; contributing approximately 298 km^2 (~1 %), 2,273 km^2 (~8 %), 6,864 km^2 (~23 %), 14,149 km^2 (~48 %) and 4,555 km^2 (~15 %), respectively (Bose et al. 2020). The composite analyses for all the bird groups together and with each group paired with the raptors also identified areas with lower probabilities of collision (with threshold; cut-off value >0.5) on turbine installations in the state. These were averaged across all groups and still showed only a small expanse of 754 km^2, i.e. ~2 % of the area of the federal state.

5. Among the turbines, some of the existing turbines were already distributed in the predicted collision risk areas; where the risk was below the threshold of 0.5 for each of the bird groups, along with some wind turbines in the approved and proposed phases of construction also planned in these areas of the state. The areas where these turbines were distributed narrowly approached the collision risk areas that had higher probabilities of collision (threshold >0.5), especially for pigeons and raptors. The expansion has already (through approved turbines) led to and will continue (through proposed turbines) to lead to a further increase of risk, although under a given threshold. Therefore, the turbines in areas with fairly lower collision probabilities could also lead to non-negligible numbers of collisions, but only the areas with collision probabilities <0.05 can be interpreted as the actual "no risk areas", and all other probability thresholds do have some risk or at least a residual risk of collision. The results from Chapter III and IV illustrate that the wind-

based renewable energy targets set for the federal state of Brandenburg can be achieved by suitably positioning the wind turbines, avoiding the predicted collision risk areas to minimize bird collisions at WTs, especially the ones with fairly lower collision probability thresholds, located particularly farther away from the ecologically sensitive distances of the prime detected land-use types. Therefore, future installation planning must be done with utmost vigilance. One such example was that of the Common Buzzards (*Buteo buteo*), frequently detected around wind turbine structures during carcass detection surveys in the federal state of Brandenburg. This built the objective of Chapter V, that aimed to better understand the deleterious effects of these collisions at their population levels, making an intersection between their assessed spatial collision risks and their regional densities in the state to identify avenues of possible spatial segregation. It was also developed on the methodological core of Chapter IV. Results of Chapter III and IV clearly showed that distances to multiple land-use types that were involved in the collision phenomena for any given bird-group; I chose to proceed from here to the objectives of Chapter V using the Boosted Regression Trees (BRT) (De'ath, 2007; Elith et al. 2008) approach instead of RF. Despite the fact that both derive benefits from ensembling, as I wanted to detect possible combinational distances to multiple land-use types influencing collisions, interactions among the distance predictors with respect to the response as the primary requisite, which was unfortunately not possible using RF. BRT, like RF, performs an exhaustive search for best predictor to split on; whereas RF searches only a small subset, boosting grows trees in series, with later trees dependent on the results of previous trees; whereas RF grows trees in parallel independently of one another.

6. According to the results, among the predictors the distances to the edges of green and open areas around settlements (distances between 1-2 km) was also found to be contributing to the collision potential, but on the contrary distances to fields contributed the least. Although a direct connection to the agricultural use does seem to exist as hunting Buzzards more often prefer fields without vegetation, assuming that higher vegetation limits the food visibility in an area, and thus a lower and lesser vegetation is more favorable for food acquisition (Penteriani and Faivre, 1997; Bergen, 2001). Suggesting, it is also highly essential to avoid the unintentional creation of attractive food habitats at the mast foot of the

turbines due to construction of small paved ways to access the turbines, e.g. due to the creation of such open areas, with a higher edge density of greater and accessible potential prey base (e.g. small mammals) is especially known to increase the collision risk for the species (Bose et al. 2019). Additional affinities to open areas are also attributed for promotion of the courtship behavior (Cerasoli and Penteriani, 1996; Penteriani and Faivre, 1997), besides recommending the deployment of wind turbines avoiding direct vicinities of areas with prey attractions, e.g. through the design and optimal use of the area, avoiding fallow lands, green and open grasslands (between 0 and 500 meters) to the turbine locations. The models also suggest maintaining a minimum distance to the fringes of wooded areas, tree groups and individual trees in recreational parks, bushlands (up to approximately 1 km) as an important planning consideration for the location of wind turbines to avoid possible collisions (Bose et al. 2020). Buzzards are area-sensitive species that occupy almost all habitats in the cultural landscape as long as there are suitable tree populations or artificial heights that function as breeding and nesting locations, as they prefer the use of several kinds of synonymous high natural and artificial perches (Glutz et al. 1989; Hubert 1993; Penteriani and Faivre, 1997; Mülner, 2000; Probst 2002), commonly at the edges of forests (Hubert 1993; Hohmann 1994; Graham et al. 1995). This preference has been attributed to the ease of access to the nests and to a need of unobstructed view of the surrounding landscape (Hubert 1993). Therefore, maintaining a minimum distance to the fringes of the forested areas, woods surrounded by fields, tree groups and individual trees in bushlands and special recreational parks and biomes is an important planning consideration for the location of wind turbines to avoid possible collisions.

7. The results also show that amongst all the interactions, substantial pairwise interactions that in combination would likely increase the sensitivity to collision risks e.g. distances to the edges of green areas around settlements showed relatively higher interactions with distances to the edges of flowing watercourses, and to the edges of special recreational parks and biotas. Highlighting distances particularly closer to the edges of recreational biotas (< 1000 meters) in combination to distances rather away from the edges of green areas around settlements (1500 meters - 2500 meters) and the edges of settlement and structures

(1000 meters - 2000 meters) of having higher chances of strike for buzzards specifically (Bose et al. 2019). The carcasses detected at the wind turbines primarily situated at such combinational distances recommend that wind turbine planning should include a free approach and departure-based technique in such cases, i.e. avoidance of raised areas adjoining areas with open landscapes serving as possible hunting grounds to ultimately reduce collision risks in these areas, especially during breeding, because buzzards prefer the vicinity of their feeding areas to be in close proximity to their nesting hides (Newton, 1990; Kenward et al. 2001a; 2001b).

8. The study could also relate the assessed collision predictions to the regional density of the target species to delineate areas of particularly higher strike susceptibility amongst the assessed collision risk areas, because of underlying substantial residing population of the species, e.g. the spatial calculation of the strike susceptibility on wind turbine installations for buzzards in the region of Brandenburg, Germany (Bose et al. 2019). Calculations of the relative strike susceptibilities between buzzard densities and their assessed collision potentials across their residing locations in the state revealed generally lower strike possibilities across majority of the assessed high collision potential areas in the state and that the collision potentials only faced relatively higher strike susceptibility (> 60 %) at some locations. The assessment identified discrete locations; parts of the districts of Oberspreewald-Lausitz, Uckermark and Havelland, where the predicted higher collision potentials overlap with significant densities of buzzards, resulting in these areas to have a higher risk of strike susceptibility (> 80 %) (Bose et al. 2019). The prime intent behind the additional approach considering the regional density trends of the target species alongside collision risk predictions, being the safeguard of populations occurring in these high-density regions, functioning as source populations, producing an excess of individuals that can flexibly compensate for losses in other regions with comparably lower densities.
9. Additionally, The study superimposed the assessed collision predictions with areas under the proposed phases of wind energy development to check for coincides; i.e. the spatial count of the number of approved and proposed wind turbines to-be deployed in the highly strike susceptible zones for buzzards, were detected to be merely 0.29% (4 turbines) of the

total (1343 turbines proposed) (Bose et al. 2019). Primary motive of the exercise being the expansion (through approved turbines) to continue (through proposed turbines) to meet the growing energy targets of the country, only by opting for any further increase under strictly lower strike susceptibility conditions. The turbines in areas with fairly lower strike susceptibilities could lead to non-negligible numbers of collisions, i.e. only the areas with strike susceptibilities between (0% - 20%) in case of assessments made for buzzards. All other strike susceptibilities (20% - 100%) would have some risk or at least a residual risk of collision (Bose et al. 2019). This approach also ensure more or less economic certainty to the wind energy developers as well, because of its relevance for the continued development of wind energy amidst conservation implications for the two worst hit species at wind turbine structures, in the state of Brandenburg; the common buzzard and the red kite (Grünkorn et al. 2017; Bose et al. 2019). Therefore, the suggested explication to the caveat is by estimating the loss in the proposed power generation output in case of the turbines still to be installed.

10. These analyses along with the intervention of suitable mitigation efforts, avoiding any further installations wherever necessary could help to lower bird casualties considerably (Bose et al. 2018; 2019; 2020). The study also superimposed the assessed collision predictions with areas under the already functional phases of wind energy development to check for coincides. These coincides enabled focusing of rigorous post construction monitoring efforts at the turbines already extant in these areas. In some cases, setting up management rules to mitigate the effects of the detected collisions (if any), by recommending for a complete shutdown/dismantle of the functional turbines installed in these areas. Along with the justified inclusion of these areas also in the bird population dynamic studies, to further our understanding regarding the deleterious consequences of collisions at the population level of birds. Eventually helping in the formulation of adequate mitigation measures, thereby helping lower the causalities considerably (Bose et al. 2018; 2019; 2020).

Although I expect the distance based recommendations to be applicable to all turbine deployment sites and the working methodology to be applicable with a case-by-case review; taking into account the different land use types and their included features in and around the sites for turbines: already deployed or to be deployed at the site, together with the detailed information regarding the target species under investigation also at the site. Since the study predominantly focuses on only the frequently-hit groups of birds and only on “direct” collisions with the wind turbine structures (Bose et al. 2018; 2019; 2020), it captures only one of the many ecological impacts of wind energy infrastructures.

Therefore, I would like to clearly and understandably state that despite the usefulness of their study for regional planning processes, the collision distribution and strike susceptibility models are neither a substitute for detailed population monitoring nor for site-specific Environmental Impact Assessments (EIAs) in the course of project planning and while interpreting the results of the study and it is highly necessary to adjust the recommendations according to the specific situations present in different study regions and to the specific situations present pertaining to the species under investigation in these study regions. The best approach is not to expect the models to be an ultimate endpoint but instead to follow it as a guide for consultation within limited resources and should not be used as a sole decision-making tool for the selection of suitable wind turbine sites in the federal state.

The replicability of the approach would additionally allow its applicability to a further wider range of taxa, enabling the determination of collision risk areas in relation to wind farm siting. Therefore, the study can assist wind energy planning by modifying itself based on the site characteristics and species ecological dependencies, varying from facility to facility basis. This flexible and iterative approach would allow better outcomes in processes of wind energy development and operations, enabling suitable adaptations of future management actions with any necessary adjustment measures as well.

6.3 Improvisations and Innovations

The outcomes of many previous studies revealed the collision risks for birds at wind turbine structures using data sourced from carcass search detection surveys and identified suitable mitigation measures to minimize the collision risk (Eichhorn et al. 2012, Bellebaum et al. 2013; Hötker et al. 2013; ; LAG VSW, 2015; Grünkorn et al 2016). They also highlighted the fundamentals of uncertainties in predicting this collision phenomena despite of increased research efforts (Madsen et al. 2015), due to the associated spatio-temporal inconsistencies associated with carcass detection surveys (Erickson et al. 2014).

Orthodox mitigation measures recommend maintain a minimum distance from breeding sites of endangered species or areas with large congregations of birds to reduce the collision risk (LAG VSW 2015). The suitability of these recommendations are justified only for the breeding seasons, as these sites are the prime activity centers (Grünkorn et al. 2017) only during that season. But, as in the case of several species the fatalities have been observed to occur outside the breeding seasons (Dürr 2015), the effectiveness of these standard recommended minimum distances from the breeding sites of species remain primarily uncertain. Additionally, with the activity of species not evenly distributed across different habitats and that their habitat use also varies throughout the years and over the years (Grünkorn et al. 2017), the recommendation of these minimum distances does not account for such associated uncertainties.

Therefore, the approach presented in this study highlighted that for species, at least the ones with frequent fatalities; their populations depend on the actual types of land use (Grünkorn et al. 2017, Bose et al. 2018, 2019, 2020), changes to which would also obviously result in changes to their breeding, feeding and resting areas. Thereby, limiting the success of the recommended minimum distances-based mitigation measures related to turbine placements, to a great extent. Now solely utilizing the spatial information of the turbines with detected carcasses in the study, I tested the combination of nearest distances they have to the different land-use types, actually giving insights into resource-based dependencies of the detected species, which in turn influences their collision phenomena at the respective turbines. The innovation of the study is based on formulation of the concept, that bird behaviors are guided by resource utilization across different land-use types, accessible at the nearest reach (minimum distances) round the year and not specifically to the breeding season only.

Not only is the approach more pragmatic in recommending the spatial placements of wind turbine structures to reduce the collision risks for birds in advent of rapidly changing land-use configurations. It also requires only a small number of carcass records to sufficiently cover most of the distances to different land-use types. These distances are suitable according to the preferential reach of the bird to procure resources, leading to possible collisions. E.g. this is similar to distribution modelling of a specialist species with a narrow niche breadth, with restricted ecological requirements, that requires limited presence data to ascertain their entire ecological niche (Rebelo and Jones, 2010).

Therefore, the study can assist wind energy planning based on the site characteristics and species ecological dependencies for resources governed by particular land-use types, varying from facility to facility basis. This flexible and iterative approach would allow better outcomes in processes of wind energy development and operations by recommending the avoidance of the areas predicted with higher risks of collisions, mandatory pre-construction monitoring in areas with predicted substantial collision risks and post-construction monitoring of extant wind turbines already installed in areas. These mitigation measures together, allows a better understanding of the collision phenomena and enabling suitable adaptations of future management actions. The caveat of this approach being the incalculable economic risk for the wind energy developers and the wind farm operators during the operational phase of the wind farm.

Keeping a check for any adverse effects on the population level of the species due to collision-based mortality being is particularly inevitable. Especially according to the current knowledge, this is relevant for the continued development of wind energy amidst conservation implications for the two worst hit species at wind turbine structures, in the state of Brandenburg; the common buzzard and the red kite (Grünkorn et al. 2017; Bose et al. 2019). Therefore, to ensure more or less economic certainty, along with minimizing the collision risk towards certain species using the approach, I suggested an explication to this caveat. I estimated the loss in power generation from the pre-existing turbines- already installed in these areas, that are recommended for a complete shutdown and dismantle and also in estimation of the loss in the proposed power generation output in case of the turbines still to be installed- in their proposed phase of development. These analyses along with the intervention of suitable mitigation efforts wherever necessary could help to lower bird casualties considerably (Bose et al. 2018; 2019; 2020).

Lastly, I also related the collision predictions to the regional density of the species to delineate areas of particularly higher strike susceptibility amongst the assessed areas to be completely devoid of any wind energy development activities. The method involved superimposing of the regional densities of the species to their previously assessed collision risk areas. Thereby delineating areas of particularly higher strike susceptibility amongst the assessed areas, because of underlying substantial residing population of the species existing in these areas. The prime intent behind this approach being the safeguard of populations occurring especially in these high-density regions, functioning as source populations, producing an excess of individuals that can compensate for losses in other regions with comparably lower densities. With the continued expansion of wind energy, this additional approach taking into account the local population trends alongside collision risk predictions was a reasonable add-on to the other suggested mitigation measures.

6.4 Limitations

The limitations of the study were common to the methodological constraints of research targeting similar objectives; foremost being the lack of spatially and temporally homogenous bird collision data from the wind turbine structures that were collected unsystematically and without uniformity in the search efforts, alongwith incomparable search protocols used for collections. Furthermore, being highly influenced by the odds of carcass persistence times due to scavenging activities and also due to the detection inadequacies of the monitoring teams, with varying detection efficiencies between researchers, across different substrates and the species of birds involved in the collisions (SNH 2010; Erickson et al. 2014). This results in the lack of true absence data, which in turn leads to weak and partial inferences from the predictor variables and biases in model estimation leading to overconfidence about precision (Kéry et al. 2010; Lahoz-Monfort et al. 2014), thereby limiting the ability to compare sites and to determine the cumulative impacts on relevant species (Hull & Muir 2010).

Data sets of collision victims are also likely to suffer from another form of imperfect species detection i.e. false positive records. It is not only difficult but also impossible to account for all the multiple influencing factors to standardize the available data on detection of fatal collisions and the resulting carcasses detected. For example, not all the birds injured by the strong turbulences or direct collisions (causing muscle ruptures, wing luxation, or bone fractures) die and fall in the immediate vicinity of the turbine they collide with. An unknown proportion still pass this situation and fly larger distances, with suffering from injuries and die later because of starvation, predation or other reasons directly related to the collision event. This way, it is impossible to estimate the proportion of birds actually hit, because each of these events would have to be detected, the type and the severity of the injury has to be registered, and the fate of the still alive, i.e. escaped, bird to be monitored. This would only result in the information about the probability to die or the probability to survive for those birds that have experienced a collision but left the area (SNH 2009).

The second group of victims are those, that can be found in the near vicinity of the turbines post the collision event. This is the proportion of birds that suffered serious injuries due to the collision or turbulence and either lost their ability to fly or died immediately.

However, even from this group only a smaller proportion can be found because of inconsistencies related to species-specific carcass persistence times, searcher efficiencies, and substratum or vegetation cover present (Erickson et al. 2014). Some of them; will simply be overlooked, unnoticed in dense vegetation, thrown out of the often-limited search range (collision caused acceleration or strong winds) and lastly eaten or carried off from the search area by predators (Bernardino et al. 2012).

These recovery probabilities are related to the distance from the turbine, size and shape of the search area, size and species of the victim (e.g. big and colorful vs. small and grey or green in grey-green winter vegetation), weather (wind, rain, snow, heat), time lag between collision and control, alertness, attention and sight of the observer, and whether only humans or humans together with detection dogs are performing the survey. Use of detection dogs can increase the probability to find a carcass substantially (Paula et al. 2011; Grimm-Seyfarth et al. 2019). Ignoring these factors can cause serious bias in the estimation of the collision probabilities, resulting in constrained estimation methods that are not applicable under general circumstances (Korner-Nievergelt et al. 2011). The severity of the problem depends on the intensity of these errors and how they correlate with the predictor variables (Lahoz-Monfort et al. 2014; Guillera-Arroita et al. 2016).

In this study, the approach used to deal with these limitations in the collision dataset was, by stratifying it according to the characteristics of the species. As the involved spatio-temporal variations associated to the dataset were already high, the separate visits were aggregated reflecting the ecology of the species. Taxonomical grouping criterion was chosen for purposes of aggregation, firstly because of morphological and ecological similarity and secondly with the aim to have sufficient individuals in the subsamples for statistical testing.

Additionally, this taxonomic stratification was also based on similar morphologies and ecological processes among the detected species. Such stratifications based on linkages between taxonomic and functional diversities defined by firstly similarities in species morphologies that determine habitat and ability to colonize, followed by physiologies influencing their adaptiveness to the habitats based on rates and efficiencies of birth, death and resource utilization (Moore, 2001) influencing their collision response at the WT structures (Bose et al. 2018). With respect to temporal limitation, as the aggregated visits were not conducted close in time but were well spread out across the ecological activities of the species through different seasons, it better reflected the total area used by the species.

Moreover, I combined all the records collected over long periods into one database, considering the timing of visits and interpretation of collisions, normally applied to conventional SDMs e.g. multiple detections records obtained from several visits/observers/detection methods, from data over years incorporated together (Bose et al. 2018; 2019; 2020).

With respect to these spatial limitations, a number of studies have already addressed the trade-offs between visiting more sites or applying more effort per visit (Guillera-Arroita et al. 2010; Guillera-Arroita and Lahoz-Monfort 2012). These studies recommend sampling a set of sites repeatedly rather than sampling many more sites with reduced effort, because with higher effort though the chances of carcass detection are higher, but there is no guarantee. Therefore, what should be done is repeated sampling and use of occupancy models that allow to qualify absence data into true absence (Bose et al. 2018; 2020).

Secondly, as fatality detections under unsystematic surveys automatically lead to a bias for more detectible species, found resting or foraging in and around the wind farms. This leads to inferences that the collision risk is highly species specific. But as there also seems to exist greater similarities between related species (Grünkorn et al. 2017, Bose et al. 2018; 2020), within these aspects of similarities, an assessment transfer of collision risks to less abundant species with scarce data is also possible (Bose et al. 2018; 2020).

Previous studies based on comparisons between the relative abundance data of the species in a region and their frequencies of carcasses detected in that region, found birds of prey to have collided frequently at the wind turbine structures (Grünkorn et al. 2017). Usually quite good data for collision victims among the birds of prey were available (Grünkorn et al. 2009; Bose et al. 2018, 2020), due to their greater carcass persistence times and the related detection efficiencies (Erickson et al. 2014), making them ideal for successful modelling and predictive purposes (Grünkorn et al. 2009; Bose et al. 2018; 2019).

Therefore, my study also suggested the utilization of the collision records specifically from the bird of prey as an exemplar. They are also already known to play a very important role as flagship and umbrella species within general nature conservation strategies, besides being critical ecosystem services providers themselves (Donázar et al. 2016). They might also be used as indicators and/or umbrella species useful for evaluating and managing mitigation measures (Moleón et al. 2007; Pérez-García et al. 2011; 2016) in a rather prospectively changing ecosystem and landscape due to human interests i.e. planning new infrastructures for wind energy harness (Donázar et al. 2016, Bose et al. 2018; 2020) in order to minimize any undesirable effects.

These detection-based limitations are although regarded as tolerable restriction for the determination of collision risks (Madsen and Cook, 2016). There are still some currently available efficient methods as well, that deal with these shortcomings. They extrapolate the carcass detections to estimate actual collision rates for purposes of future projections, to assess the potential effects of collisions on the population trend of species (Bellebaum et al. 2013). Such assessments were unfortunately beyond the scope of this study, due to the unavailability of systematic presence/absence carcass detection records and the inaccessibility of the species abundance estimates from the study region. Therefore, SDMs based on presence-only datasets were the lone possible way in this case.

Conclusively, the best approach would not be to expect the models to be the ultimate endpoint, but instead following it as a beginner's guide to focus on monitoring efforts around turbines within the limited available resources, along with more research and assessment with multiple species i.e. application of joint SDMs etc., making the findings more relevant for planners and policy makers.

6.5 Future research

Conclusively, as the study identified the potential collision risk areas for birds in the landscape prior to wind farm installations, by the determination of sensitive distances to particular land-use types that promote resource-procurement related collision risk amongst birds.

The recommendation of avoidance of these sensitive distances assists the environmental impact assessment studies at proposed wind farm locations prior to installations of wind turbines. The study can also assist in highlighting the extant turbines to be enrolled for compulsory post-construction carcass search monitoring surveys in cases turbines have already installed in the assessed collision risk areas. Additionally, delineating areas of particularly higher strike susceptibility amongst the assessed areas, because of underlying substantial residing population of the species existing in these areas.

Furthermore, the study also assisted in estimating the loss in power generation from the extant turbines- already installed in these areas, that are recommended for a complete shutdown and dismantle and also in estimation of the loss in the proposed power generation output in case of the turbines still to be installed- in their proposed phase of development, in the collision risk areas. These analyses along with the intervention of suitable mitigation efforts wherever necessary could help to lower bird casualties considerably.

The replicability of the approach would additionally allow its applicability to a further wider range of taxa, enabling the determination of collision risk areas in relation to wind farm siting in general. While the distance based recommendations could be used in spatial planning, on a case-by-case review, taking into account the site characteristics and species ecological dependencies, varying from facility to facility, making it necessary to adjust the recommendations to the specific situation of each region.

This flexible and iterative approach would allow better outcomes in processes of wind energy development and operations, enabling suitable adaptations of future management actions.

The study has already influenced another project called TURBATS. This project extends research beyond the project “Bird & Blades”, to check the applicability of the designed methodologies to perform comparative analysis of the impacts of wind energy development on bats, particularly in the landscapes between Poland and Germany. The study utilizes a similar approach of species distribution modelling for the analyses of the available bat collision records from Western Poland and Eastern Germany, against the distances between and within multiple land-use types to the affected wind turbines in the study region.

This will allow the identification of areas with the highest probability of bat collisions as well as provide distance-based recommendation for turbine installations. Together, as a basis for improving the regional planning in the landscape to ensure that wind energy development has less impact on regional, transboundary, and migrating populations of bats. Germany being a world leader in wind energy development, with an approximately 62 GW of currently installed capacity (thewindpower.net 2020).

While with substantially less wind energy production from the neighboring country of Poland, with a current capacity of approximately 6 GW (thewindpower.net 2020) only, anticipating further investments in this direction (EWEA 2015), directing the project to be a relevant contribution for establishing future solutions for sustainable management of the wind energy wildlife conflict, whilst Germany serving as a case study to forecast the situation in Poland in the coming decades.

Chapter VII: References

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Chapter VIII: Supplementary Information

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Annex: Figure A8:**:** Exploration of the mechanistic relationships and interaction between Raptors collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/pseudo-absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)

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Annex: Figure A10 & A11: The relative contributions (%) of the (DELV) predictor variables for BRT full and simplified models. Developed with cross-validation on data from 332 sites and a tree complexity of 12 and 10 respectively. The full model was fitted with 12 predictors and least contributing 2 were removed and the simplified model was fit with the remaining 10 predictors.

Annex: Table A1: Relevant first five out of 12 axes of the ENFA with their eigenvalues (in brackets) and the predictor variable coefficients of the worst hit bird-groups at wind turbines for the Federal State of Brandenburg, Germany

**The positive or negative sign is relevant for the first axis coefficients, but in the following axes only the absolute value of coefficients is considered. The greater the absolute value of the marginality coefficient, the more this variable contributes to the group's marginality factor. Absolute values ≥ 0.40 are considered strongly influential. The +/- prefixes of the predictor variable require a flip in interpretation of these strongly influential variables. The negative coefficients indicate that the distances of the land-use type to the collision sensitive niche was less than what was globally available in the study area, and the positive coefficients indicate that the collision sensitive niche for the particular bird-group was farther away from the land-use type than the average distance available across the sample area. The percentages in parentheses indicate the amount of total specialization accounted for by each factor.*

		Marginality	**Specialization**			
	Variables	**Factor 1 (8.913)**	**Factor 2 (28.076)**	**Factor 3 (11.445)**	**Factor 4 (7.262)**	**Factor 5 (6.301)**
Buntings	**Bushlands**	0.22	0.11	-0.05	0.30	-0.38
	Fields	-0.44	-0.64	-0.03	0.04	0.33
	Forests_forestry	0.64	0.18	-0.04	-0.02	0.13
	Flowing_watercourses	0.11	0.49	-0.64	-0.30	-0.23
	Green_areas_settlements	0.26	0.00	-0.01	-0.37	0.59
	Grass_forbs	0.34	0.08	0.08	-0.14	-0.34
	Ruderal_areas	0.20	0.32	0.04	0.49	0.14
	Shrublands	0.15	-0.24	-0.06	-0.09	0.34
	Special_biotas	-0.02	-0.25	-0.66	0.45	0.17
	Settlements_structures	0.08	0.19	0.21	0.26	0.11
	Still_watercourses	0.13	0.21	-0.20	-0.25	0.14
	Wetlands	0.25	-0.05	0.26	0.29	0.12

	Variables	Factor 1 (11.786)	Factor 2 (31.638)	Factor 3 (18.218)	Factor 4 (7.910)	Factor 5 (6.662)
Crows	Bushlands	0.26	-0.20	0.00	0.35	0.15
	Fields	-0.37	-0.31	0.60	-0.39	-0.35
	Forests_forestry	0.47	-0.03	0.17	-0.15	-0.23
	Flowing_watercourses	0.02	-0.74	-0.44	-0.27	0.02
	Green_areas_settlements	0.42	0.02	-0.05	-0.35	-0.01
	Grass_forbs	0.40	-0.15	0.02	0.15	-0.23
	Ruderal_areas	0.24	-0.14	0.31	-0.06	0.21
	Shrublands	0.06	0.39	0.02	-0.43	0.13
	Special_biotas	0.05	-0.14	0.17	-0.23	0.65
	Settlements_structures	0.24	-0.18	0.27	0.15	0.22
	Still_watercourses	0.22	0.15	-0.33	-0.44	-0.47
	Wetlands	0.25	0.20	0.32	0.15	-0.02

	Variables	Factor 1 (6.567)	Factor 2 (29.454)	Factor 3 (14.899)	Factor 4 (8.476)	Factor 5 (6.520)
Larks	**Bushlands**	0.26	0.16	0.05	0.04	0.20
	Fields	-0.40	0.76	-0.09	0.16	0.10
	Forests_forestry	0.58	0.12	-0.32	-0.04	0.06
	Flowing_watercourses	0.05	-0.43	-0.24	0.71	-0.24
	Green_areas_settlements	0.29	0.08	-0.35	-0.30	-0.08
	Grass_forbs	0.43	0.13	-0.02	0.00	-0.07
	Ruderal_areas	0.25	0.13	0.28	0.36	0.39
	Shrublands	0.16	0.12	0.64	-0.10	-0.30
	Special_biotas	-0.08	-0.28	-0.15	-0.30	0.65
	Settlements_structures	0.14	0.07	0.12	0.33	0.13
	Still_watercourses	0.14	0.20	-0.14	-0.18	-0.35
	Wetlands	0.20	0.12	0.40	0.06	0.27

	Variables	Factor 1 (11.348)	Factor 2 (21.641)	Factor 3 (9.493)	Factor 4 (6.858)	Factor 5 (3.862)
Pigeons	Bushlands	0.22	-0.05	0.07	-0.14	0.18
	Fields	-0.45	-0.36	0.61	-0.15	-0.05
	Forests_forestry	0.47	-0.18	0.11	-0.06	-0.32
	Flowing_watercourses	-0.04	-0.25	-0.45	-0.61	-0.01
	Green_areas_settlements	0.36	-0.28	0.20	0.12	-0.26
	Grass_forbs	0.38	-0.24	0.05	-0.05	0.44
	Ruderal_areas	0.36	0.28	0.33	-0.28	0.21
	Shrublands	0.05	0.24	0.15	0.37	0.43
	Special_biotas	-0.08	0.33	0.34	-0.26	0.08
	Settlements_structures	0.27	0.33	0.05	-0.23	-0.51
	Still_watercourses	0.16	-0.49	-0.24	0.47	0.14
	Wetlands	0.12	0.20	0.24	-0.12	0.29

	Variables	Factor 1 (4.861)	Factor 2 (15.558)	Factor 3 (5.998)	Factor 4 (4.942)	Factor 5 (3.328)
Raptors	**Bushlands**	0.24	0.06	-0.02	0.15	-0.19
	Fields	-0.41	-0.79	-0.32	0.09	0.11
	Forests_forestry	0.50	-0.28	-0.08	-0.17	-0.07
	Flowing_watercourses	0.07	-0.35	0.86	-0.02	0.16
	Green_areas_settlements	0.40	-0.24	0.01	0.03	0.40
	Grass_forbs	0.33	-0.13	0.04	-0.02	-0.19
	Ruderal_areas	0.20	-0.11	-0.19	0.40	-0.15
	Shrublands	0.06	0.24	-0.17	0.24	0.74
	Special_biotas	-0.04	-0.01	0.07	0.60	-0.02
	Settlements_structures	0.24	-0.10	-0.11	0.10	-0.11
	Still_watercourses	0.22	-0.08	-0.02	-0.50	0.33
	Wetlands	0.31	0.06	-0.26	0.32	-0.15

Annex: Table A2: Discriminant factor coefficients between the collision environmental envelopes between every pair of the worst hit bird-groups at wind turbine structures in the Federal State of Brandenburg.

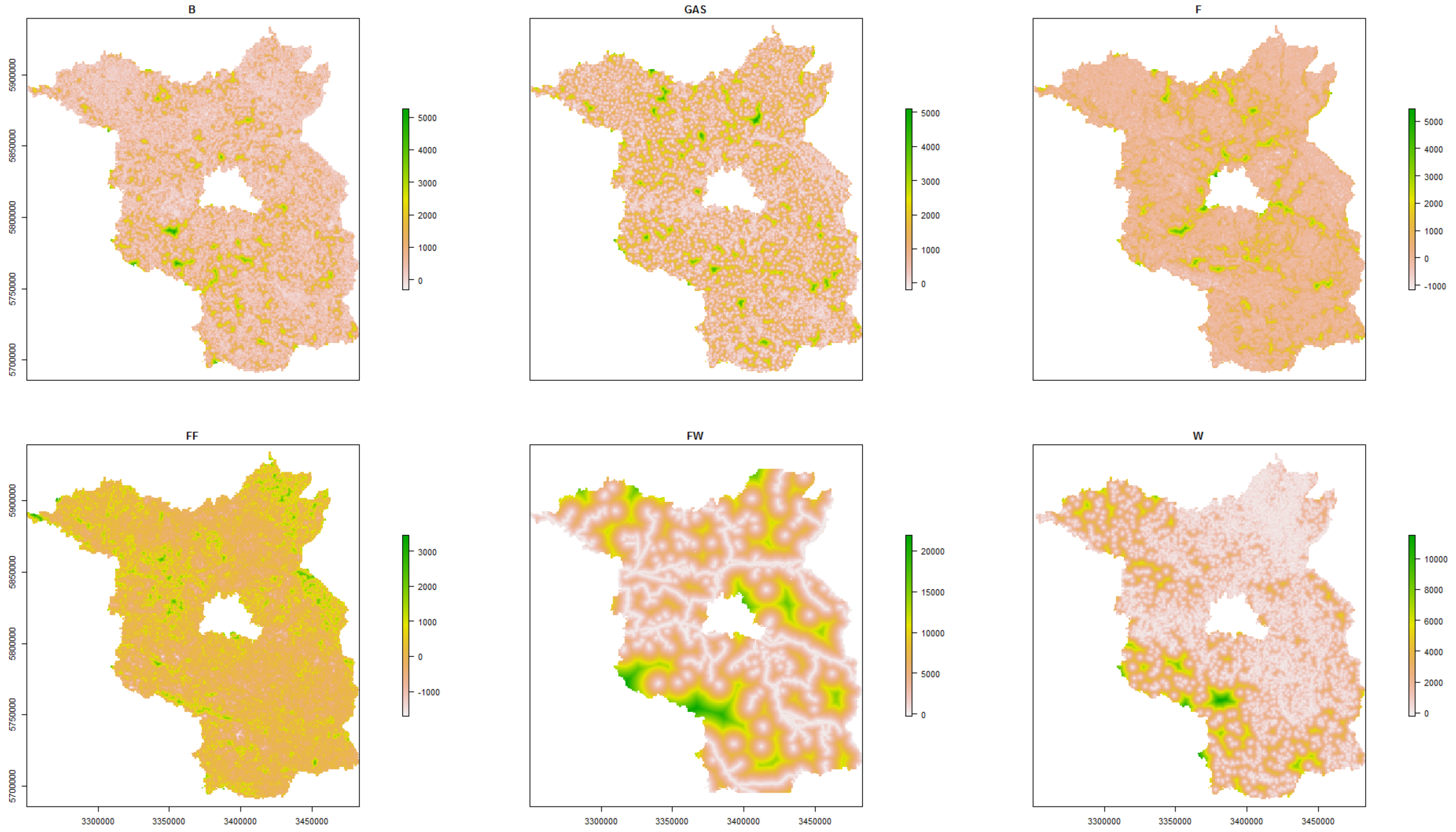
Positive values (≥0.2) indicate variables favor the collision environmental envelope of the first bird-group of the pair, and the negative values (≤ -0.2) favorable that of the latter.

DELV	Bunting & Crows	Buntings & Larks	Buntings & Pigeons	Buntings & Raptors	Crows & Larks	Crows & Pigeons	Crows & Raptors	Larks & Pigeons	Larks & Raptors	Pigeons & Raptors
Bushlands	-0.199	0.171	-0.017	0.006	-0.231	0.201	-0.281	-0.185	0.028	0.106
Fields	-0.217	-0.22	-0.247	-0.228	-0.196	0.487	0.073	-0.121	-0.019	-0.307
Forests_forestry	0.152	-0.129	-0.293	0.232	0.032	-0.109	-0.116	0.181	-0.029	0
Flowing_watercourses	0.225	-0.387	-0.315	0.236	0.328	0.3	0.427	0.379	-0.495	-0.321
Green_areas_settlements	-0.391	0.104	0.183	-0.457	-0.193	-0.055	-0.379	-0.008	-0.383	-0.047
Grass_forbs	-0.054	0.228	-0.034	-0.009	0.373	0.115	-0.105	0.512	-0.227	-0.04
Ruderal_areas	-0.332	0.324	0.391	-0.164	-0.201	-0.378	-0.485	-0.199	-0.023	0.581
Shrublands	0.455	0.283	-0.347	0.345	0.209	-0.206	0.05	0.219	0.059	-0.063
Special_biotas	0.141	-0.323	-0.411	0.409	0.011	0.034	-0.182	-0.098	0.235	0.005
Settlements_structures	-0.398	0.338	0.499	-0.366	-0.262	-0.236	-0.125	-0.299	-0.102	0.224
Still_watercourses	0.238	-0.117	-0.016	-0.382	0.559	0.473	0.364	0.552	-0.558	-0.574
Wetlands	-0.362	0.525	0.166	-0.191	-0.398	-0.372	-0.383	-0.143	0.417	0.258

Annex: Table A3: Linear discriminant coefficients and proportion of variance explained by each axis.

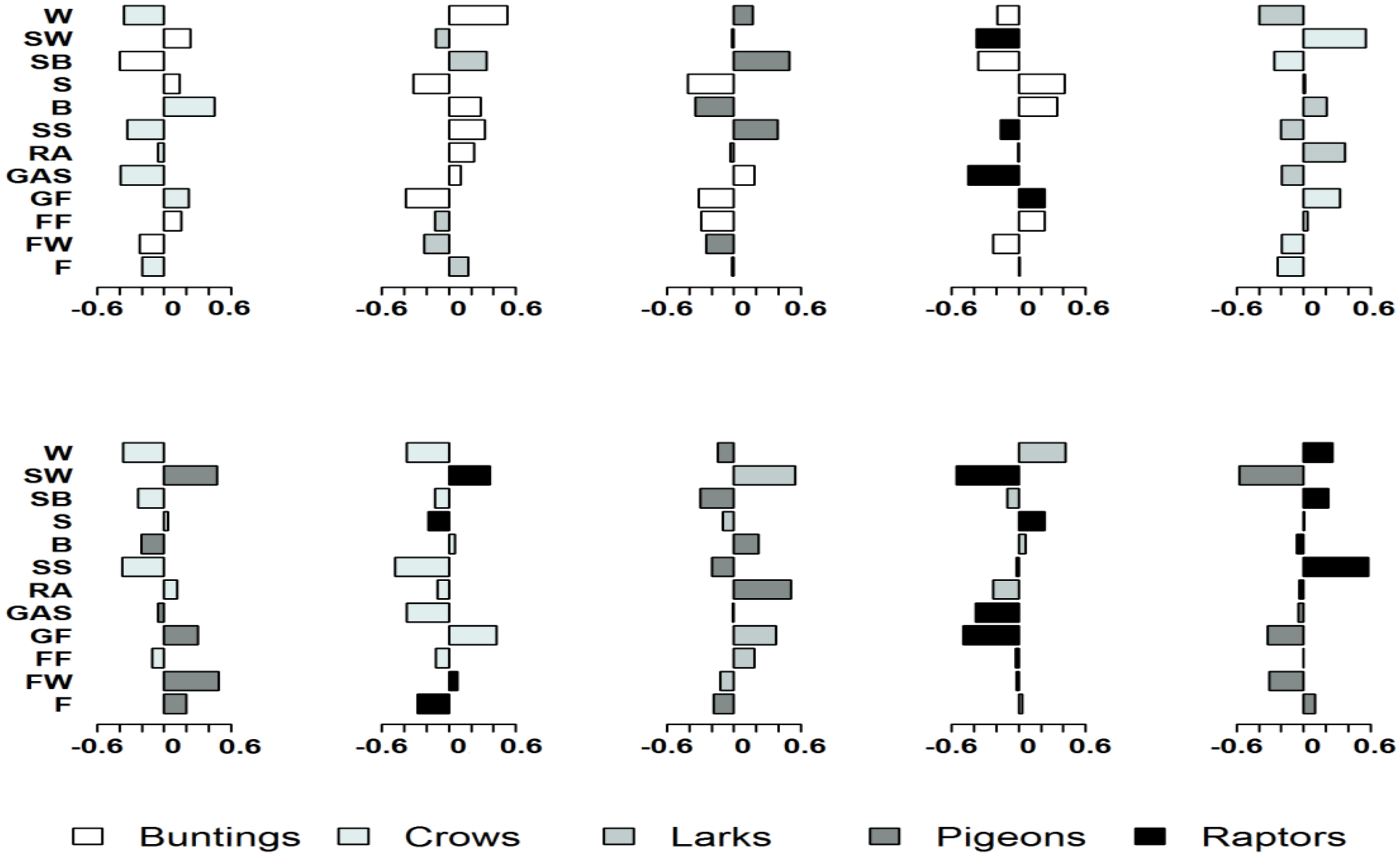
Coefficients	LD1	LD2	LD3	LD4	LD5
Bushlands	0.00032	-0.00002	0.00065	0.00024	0.00053
Fields	-0.00190	-0.00130	-0.00200	0.00055	-0.00140
Forests_forestry	-0.00047	-0.00100	-0.00044	0.00033	-0.00021
Flowing_watercourses	-0.00027	0.00008	-0.00013	0.00009	0.00022
Green_areas_settlements	0.00069	-0.00076	-0.00120	0.00022	0.00059
Grass_forbs	-0.00073	-0.00140	0.00063	0.00210	0.00110
Ruderal_areas	0.00004	-0.00007	0.00002	-0.00003	0.00001
Shrublands	-0.00010	-0.00006	-0.00002	-0.00001	-0.00017
Special_biotas	0.00004	-0.00030	-0.00005	-0.00047	0.00020
Settlements_structures	0.00120	0.00043	-0.00051	0.00043	-0.00180
Still_watercourses	0.00009	0.00059	0.00023	0.00068	0.00027
Wetlands	0.00003	-0.00041	-0.00030	-0.00011	-0.00026
Proportion of group variance	***0.48***	***0.25***	***0.16***	***0.07***	***0.04***

Annex: Figure A1: Distance to edge presentations of land-use variables in the Federal State of Brandenburg.



[1]Acronyms corresponding to the predictor variables are described in Table III. 1.

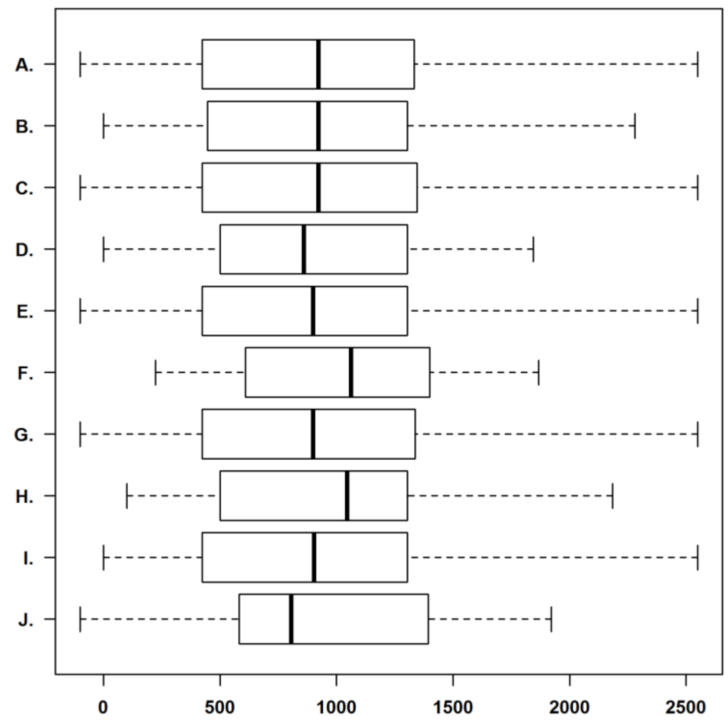
Annex: Figure A2: Predictor variables discriminant coefficients between the collision environmental envelopes of every pair of the worst hit bird-groups at wind turbine structures in the Federal State of Brandenburg.



[1]*Acronyms corresponding to the predictor variables are described in Table III. 1.*

Annex: Figure A3: Distance distributions of turbines without (A, C, E, G and I) and with fatalities (B, D, F. H, and J) for the worst hit bird-groups with regards to the predictor variables: Raptors, Pigeons, Larks, Crows and Buntings respectively.

[1]*Acronyms corresponding to the predictor variables are described in Table III. 1.*



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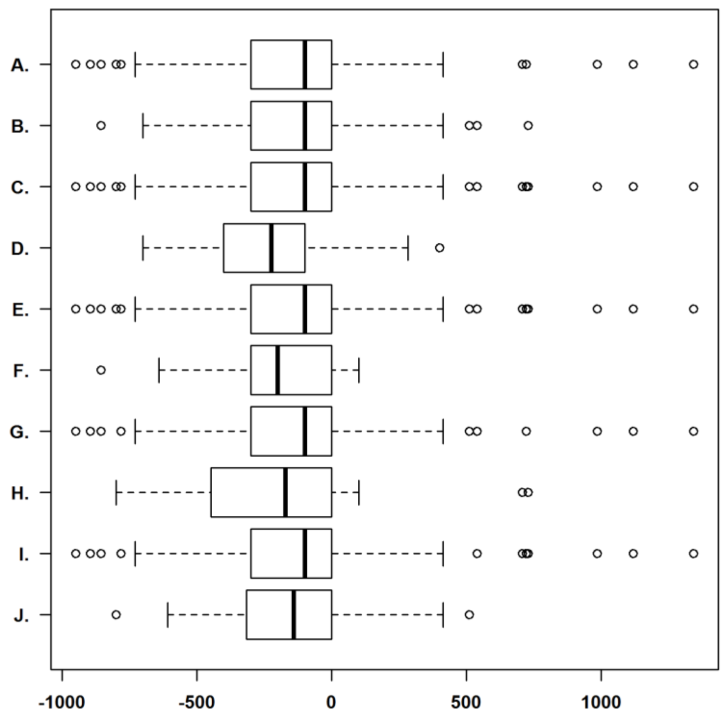

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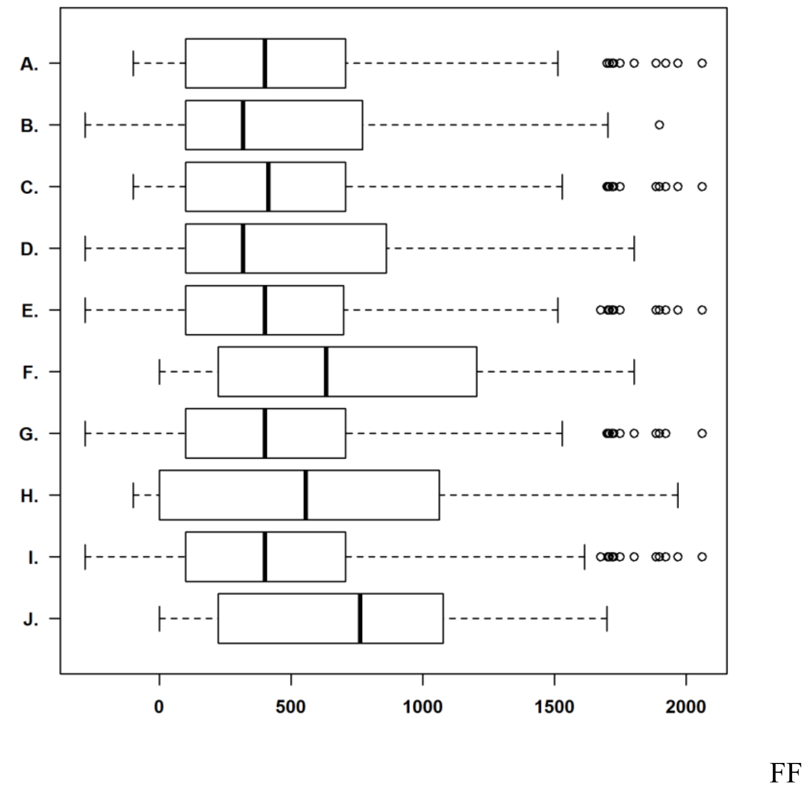
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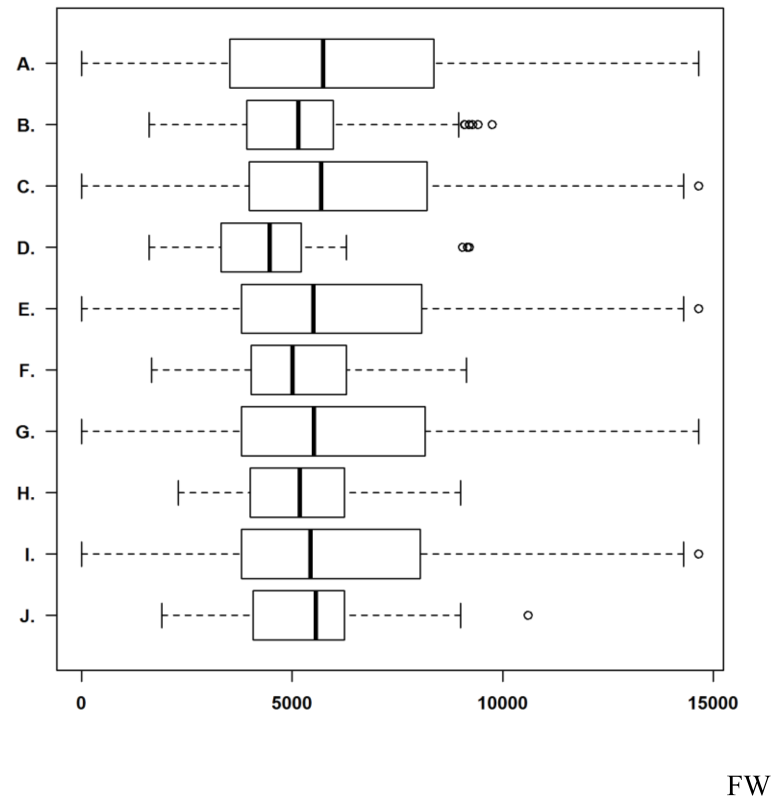
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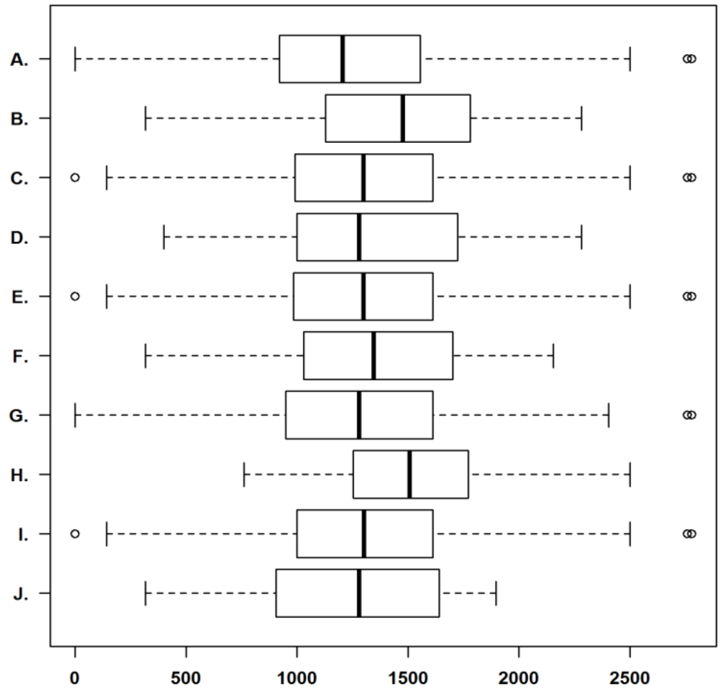
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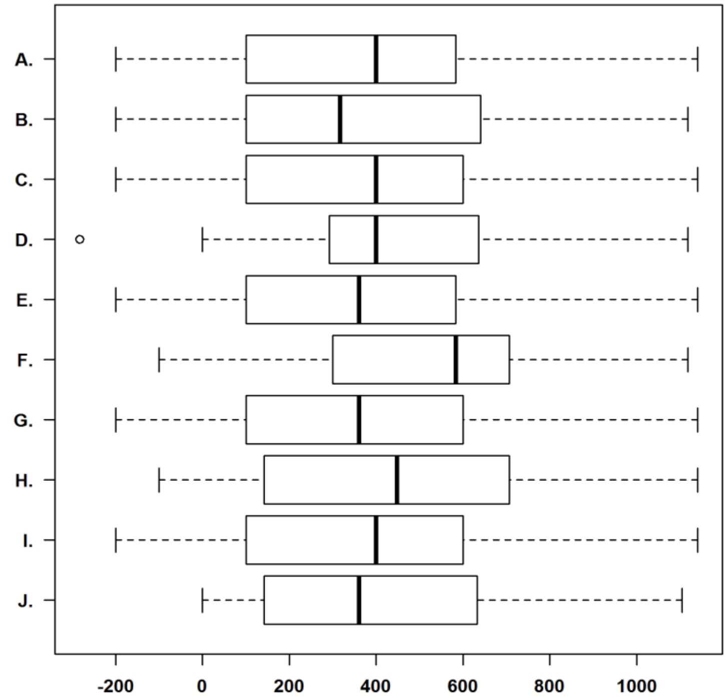
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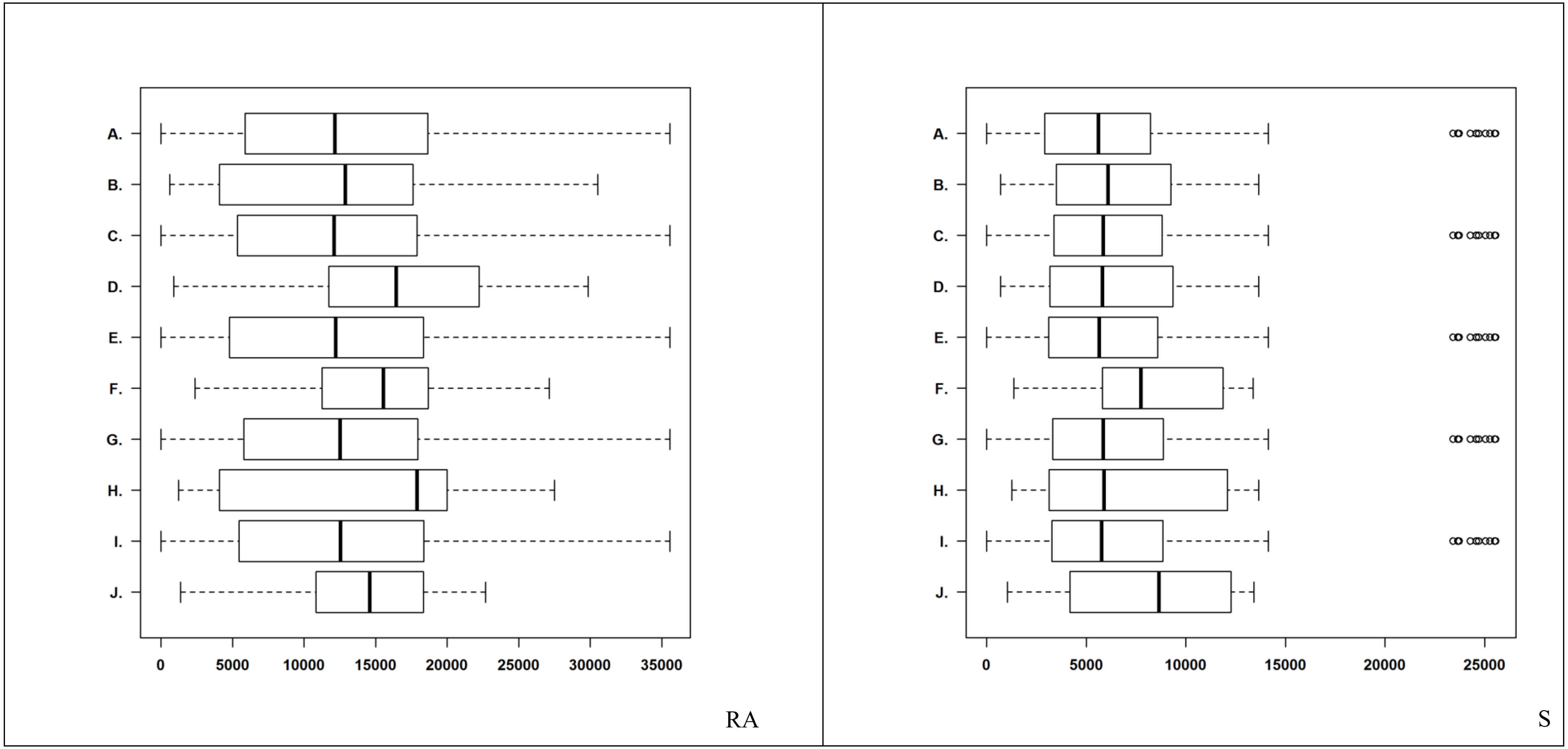
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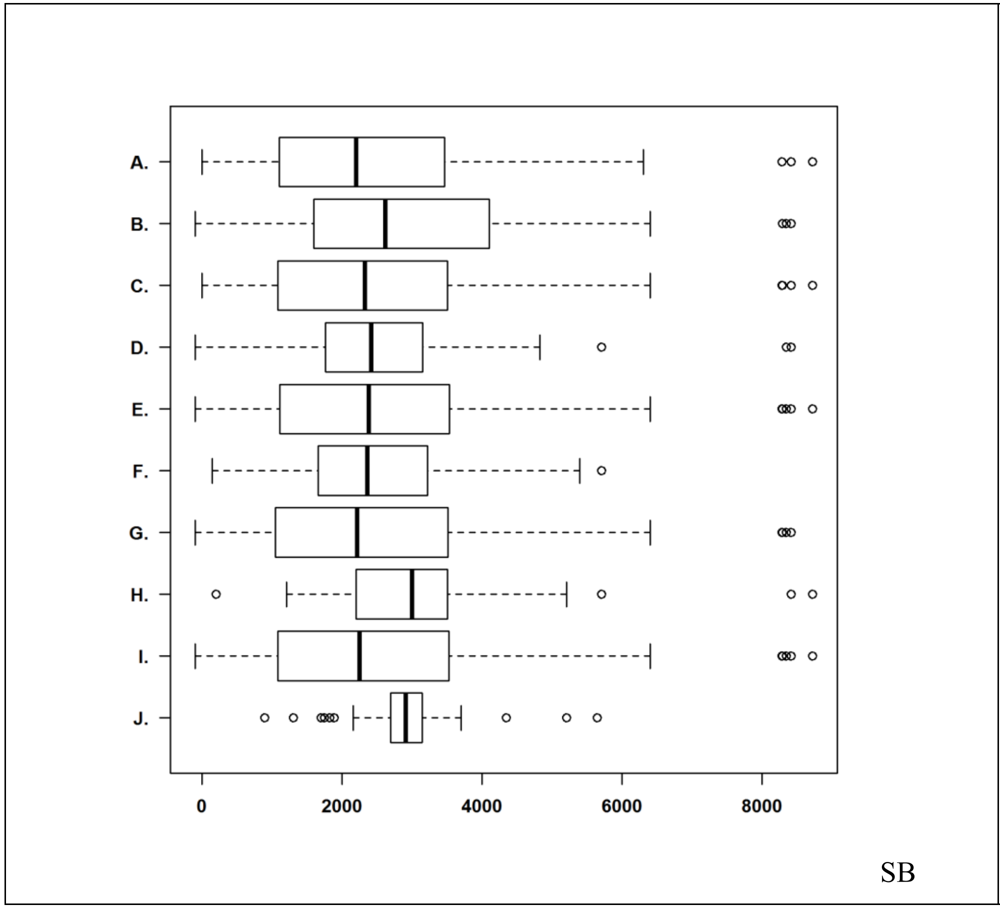
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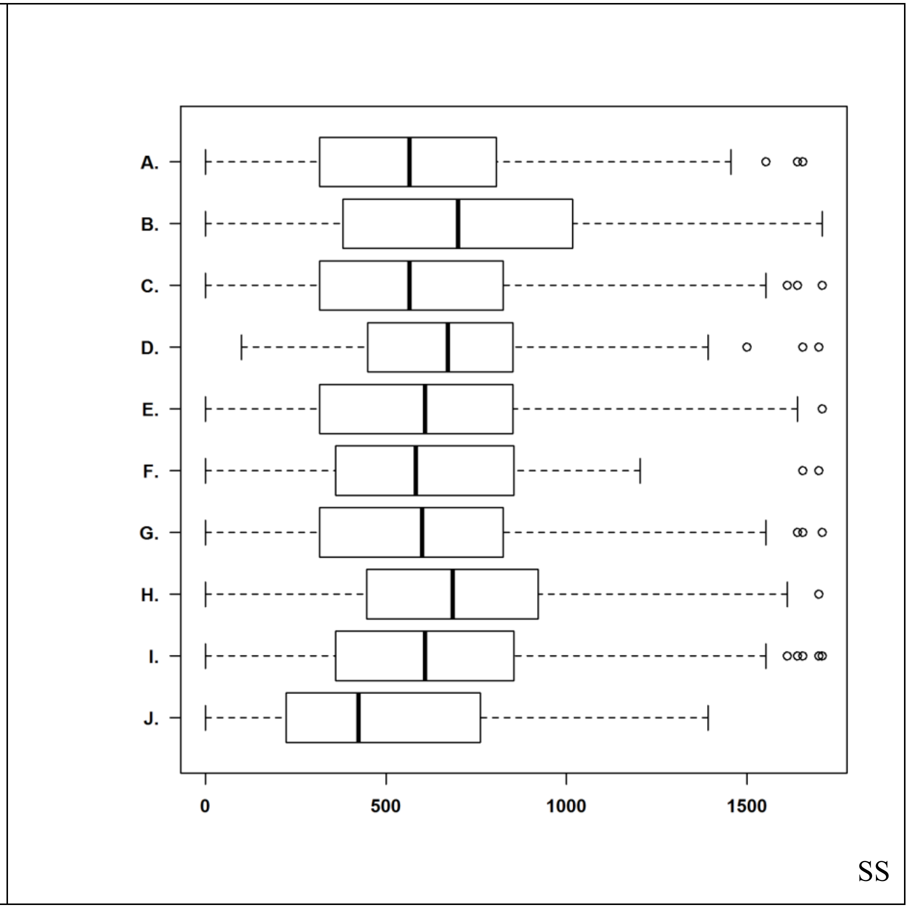
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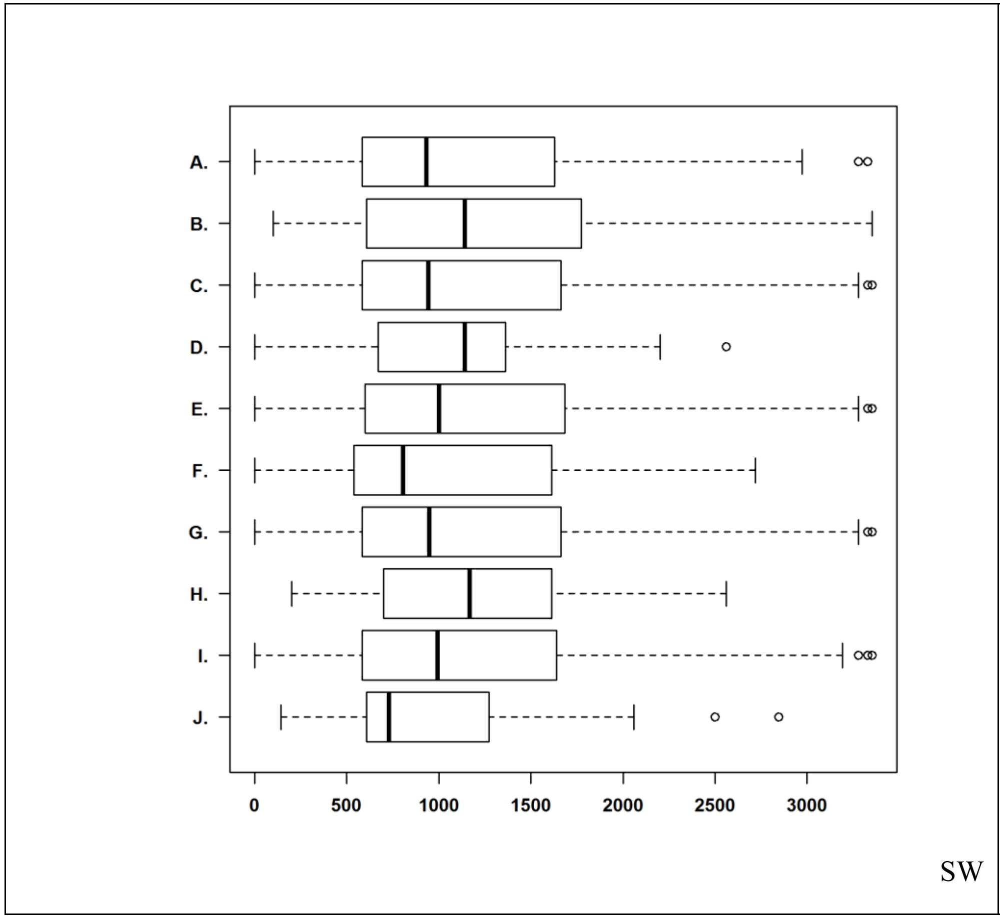
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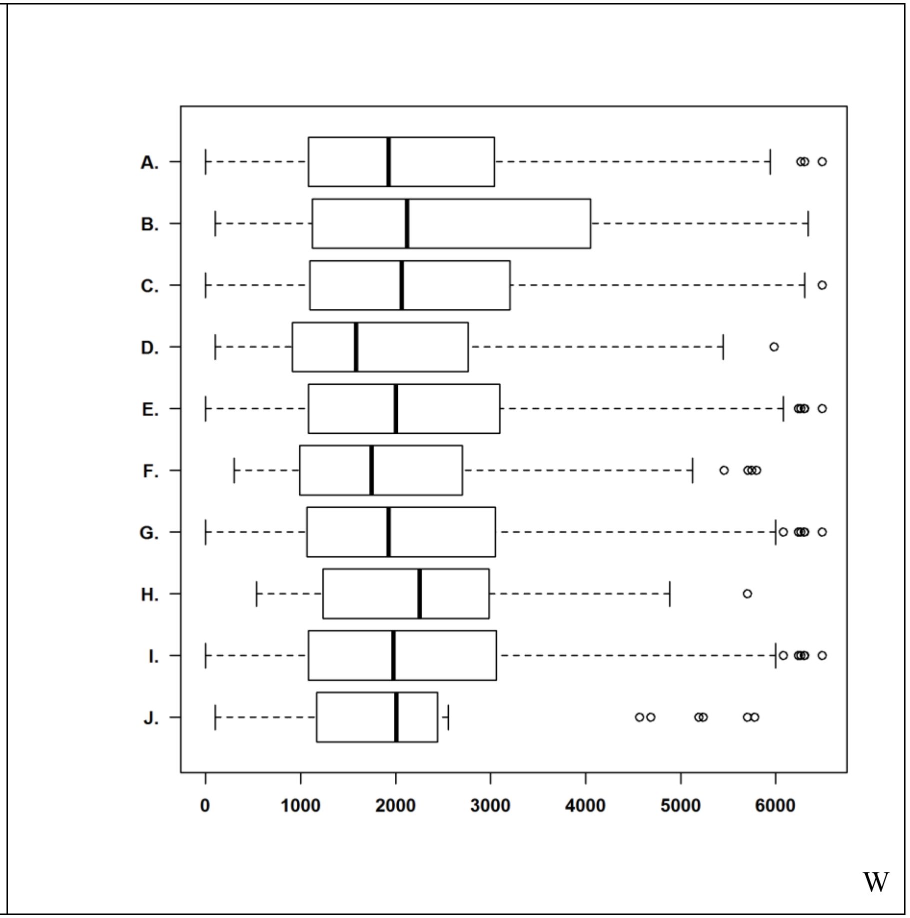
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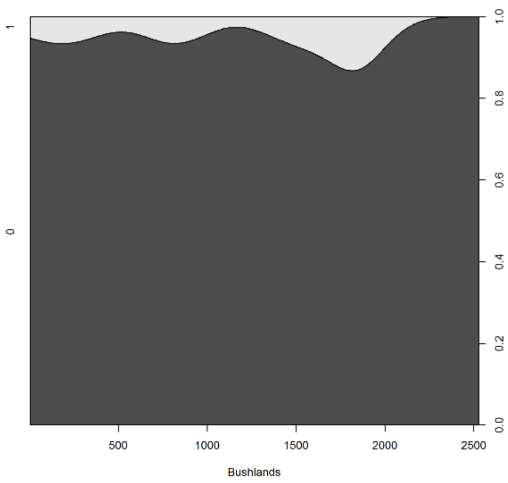
Annex: Figure A4: Exploration of the mechanistic relationships and interaction between Buntings collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)



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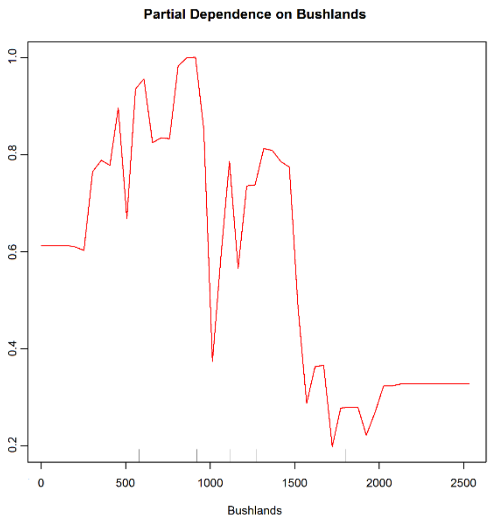
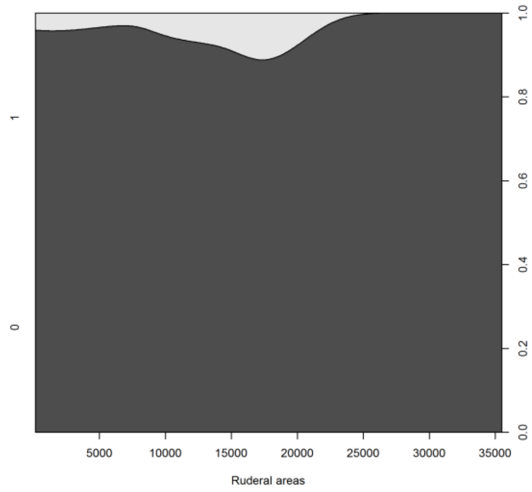
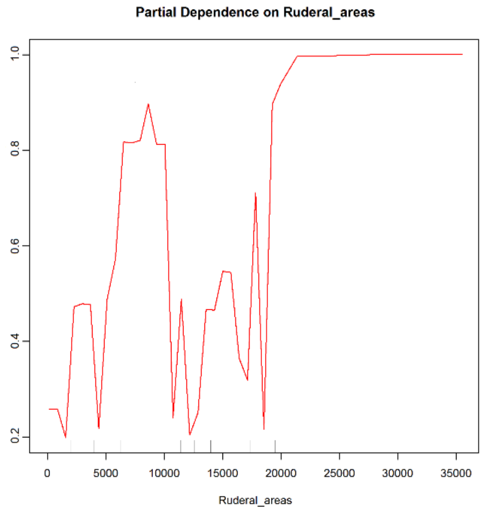


B-7



RA-13



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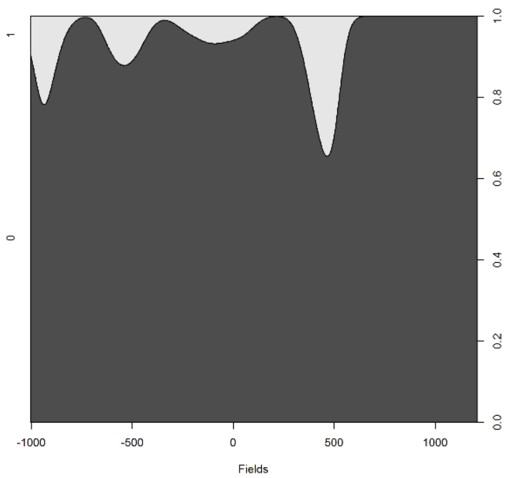

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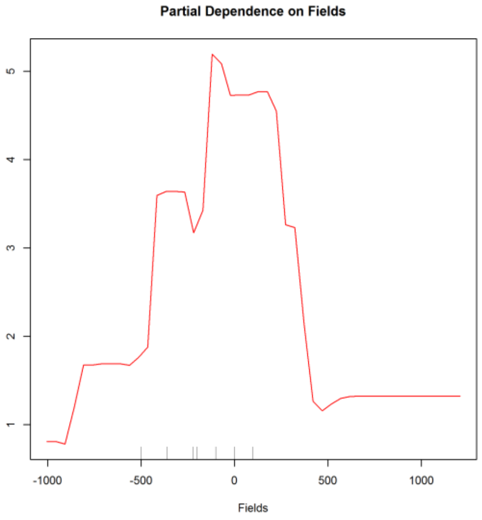

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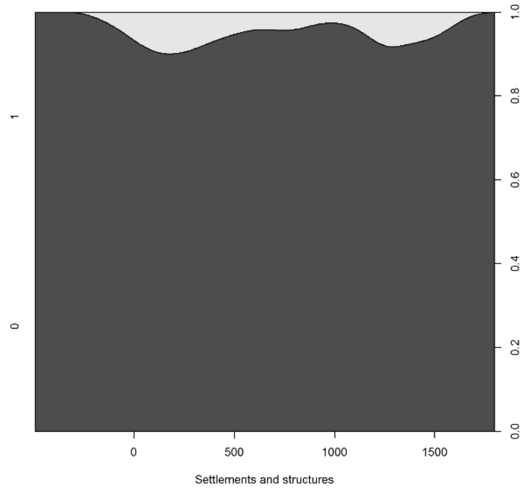

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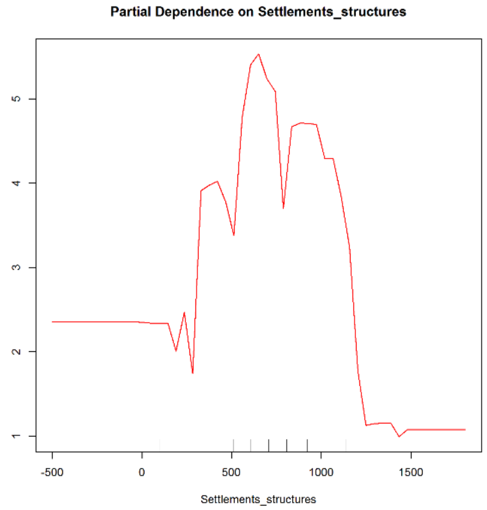

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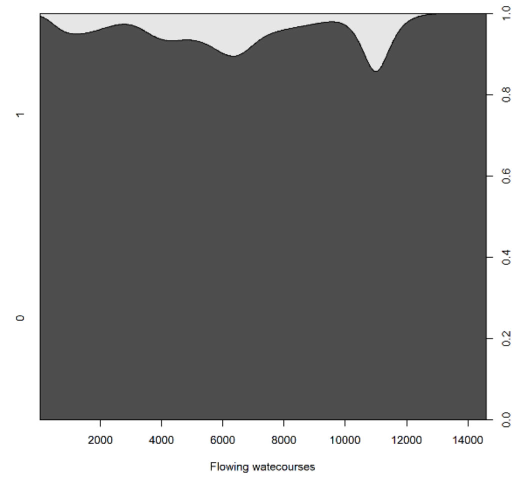

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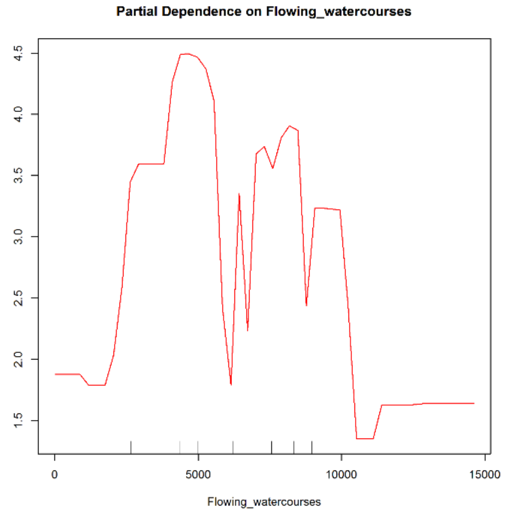

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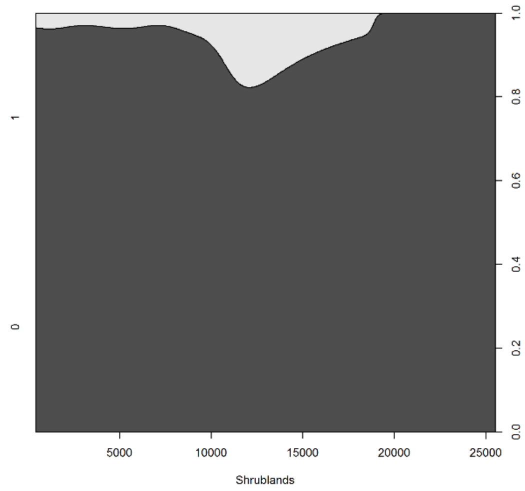

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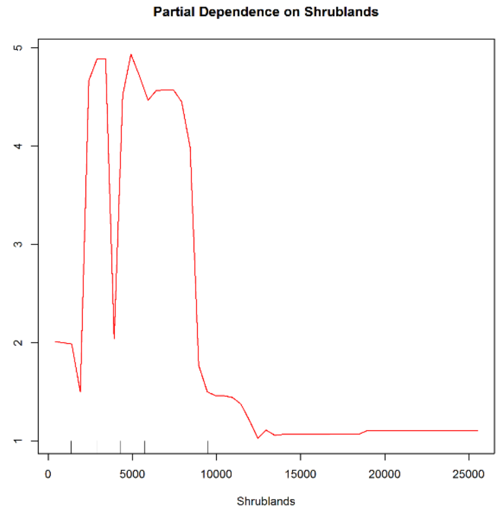

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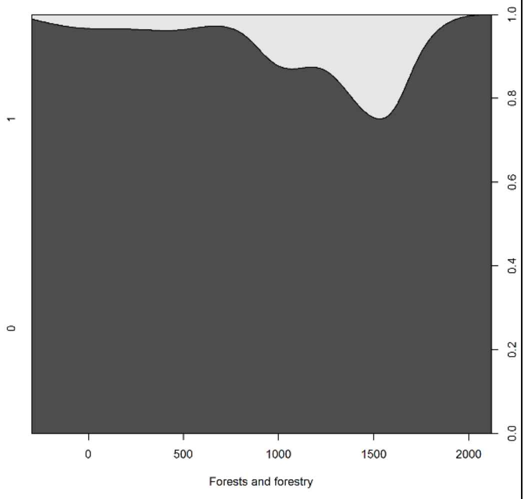

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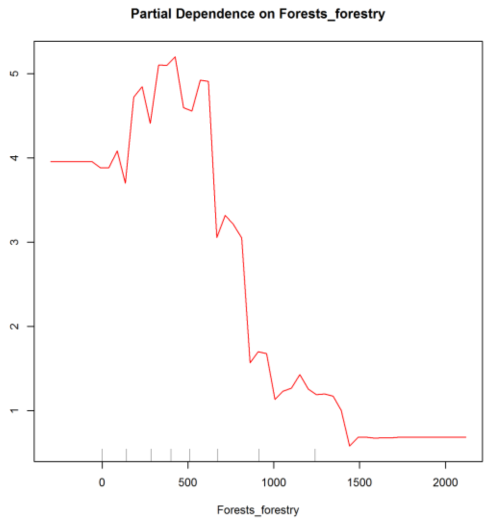

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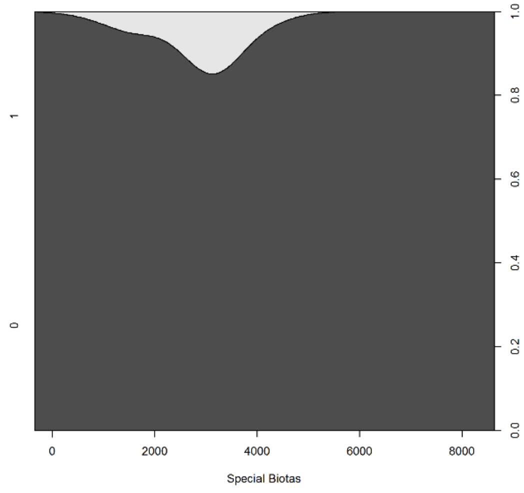

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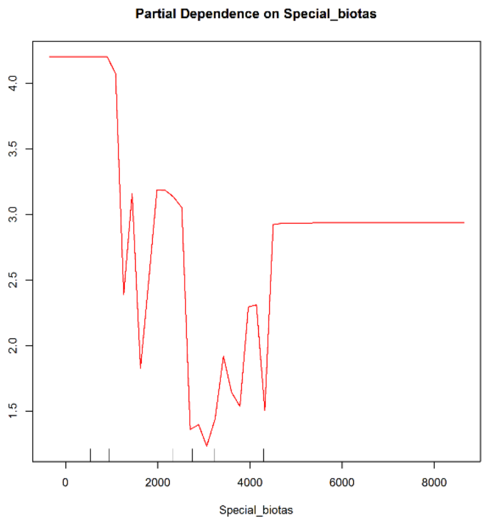

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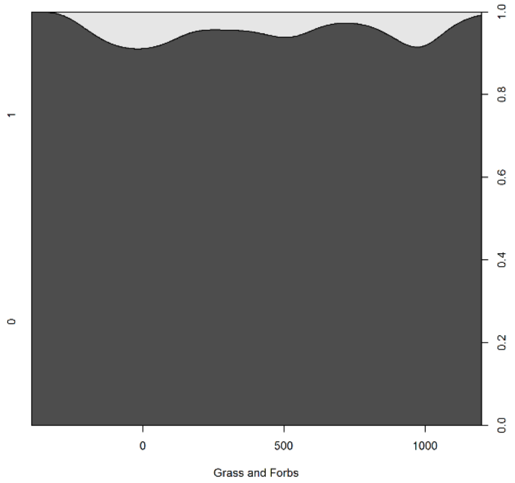

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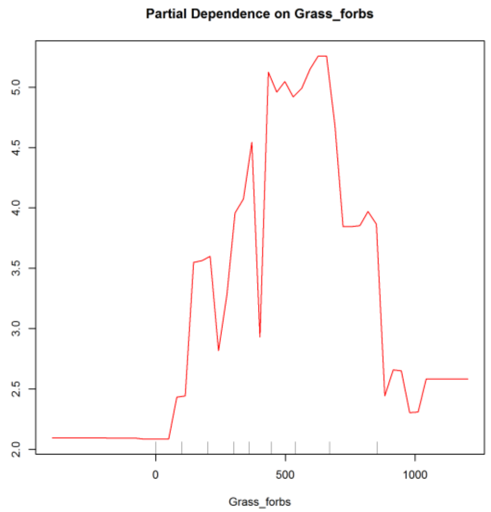

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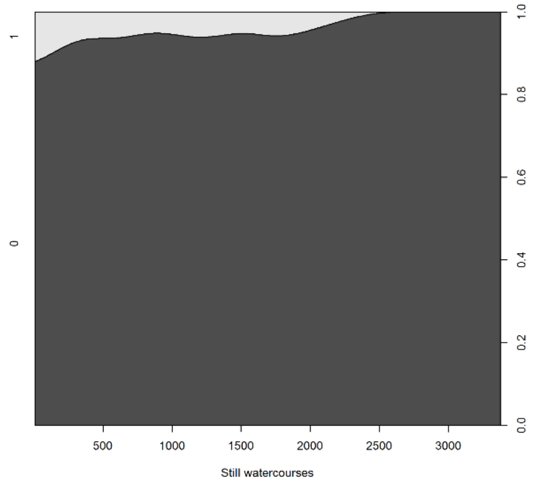

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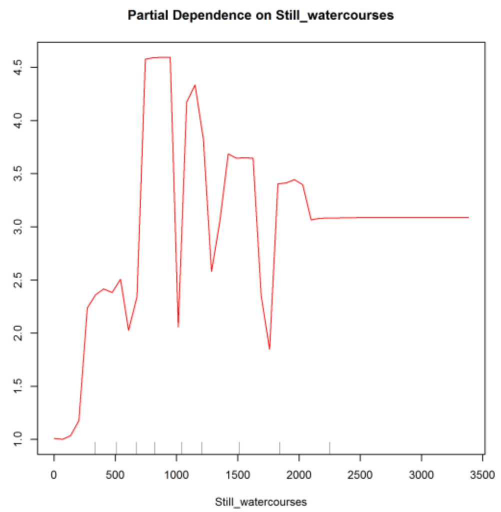

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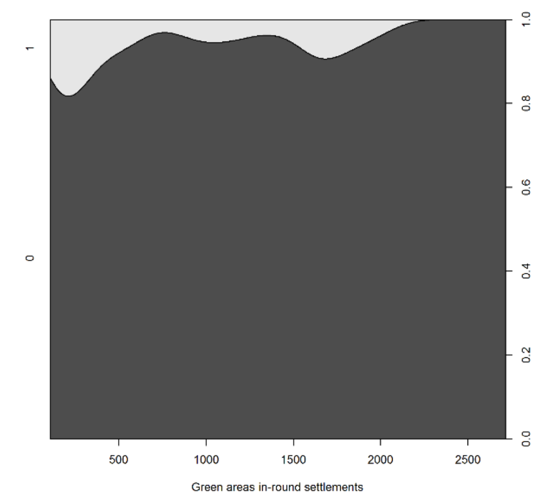

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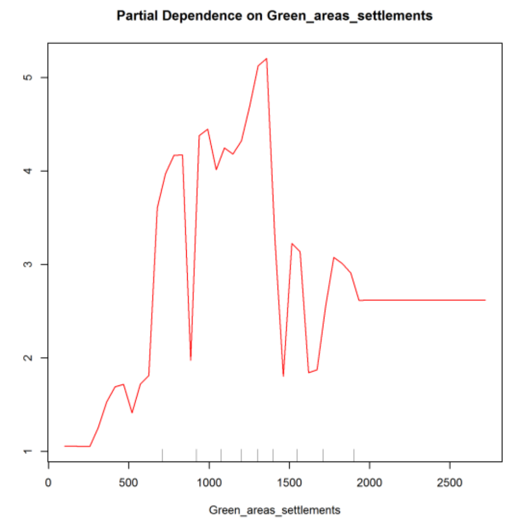

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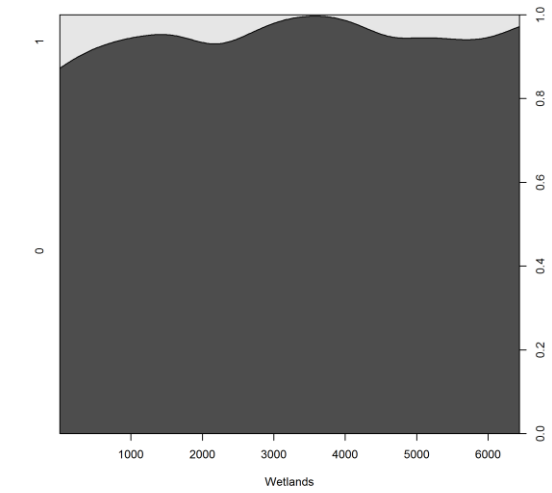

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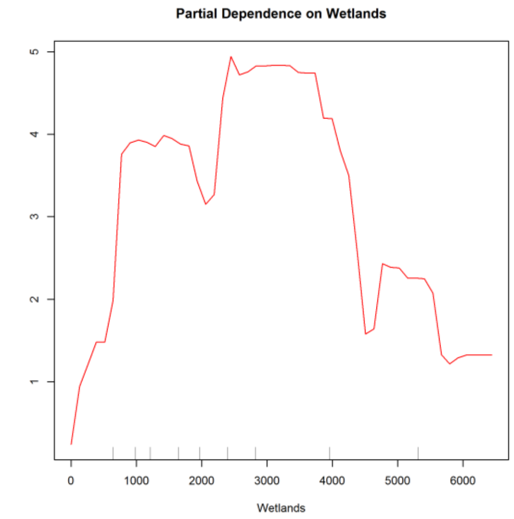
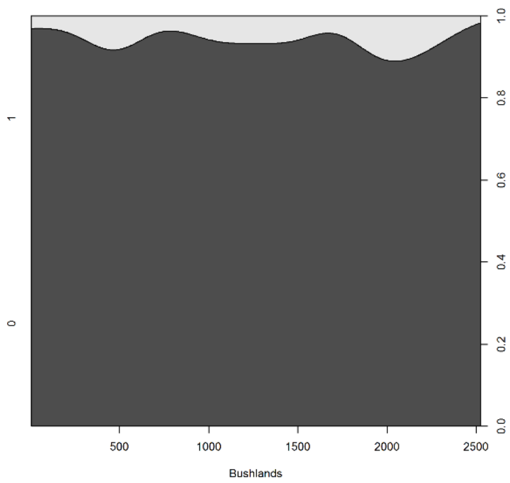


W-24

Annex: Figure A5: Exploration of the mechanistic relationships and interaction between Crows collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)



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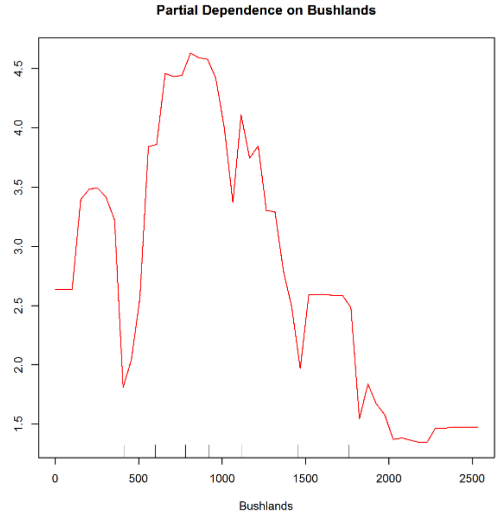

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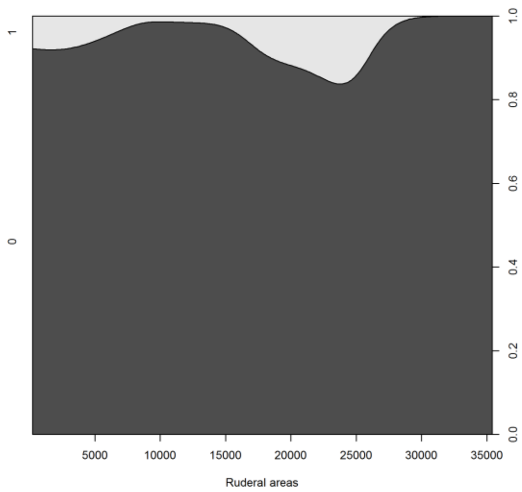

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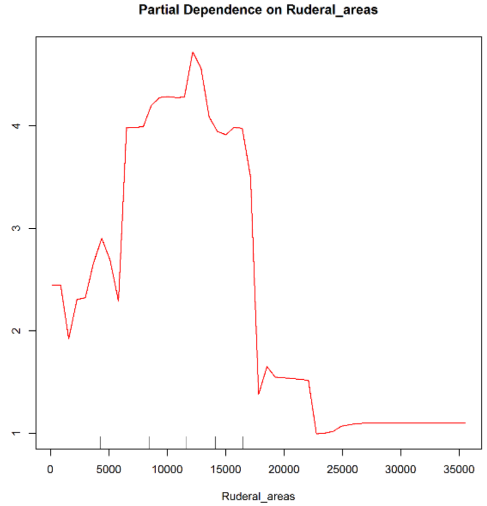

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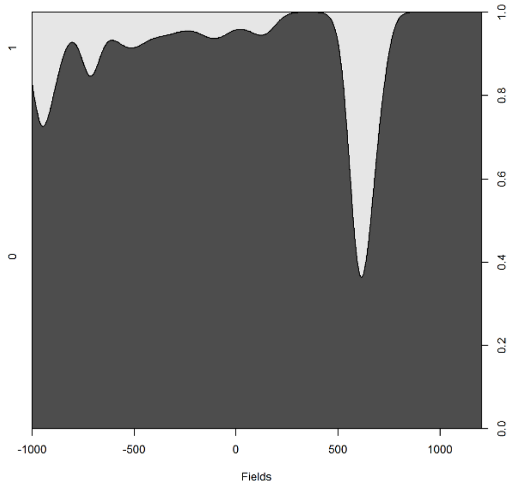

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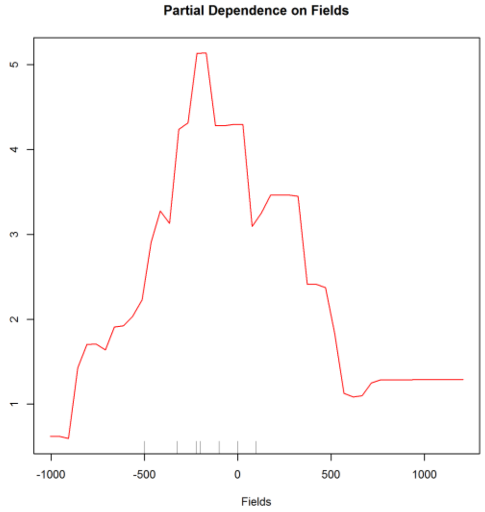

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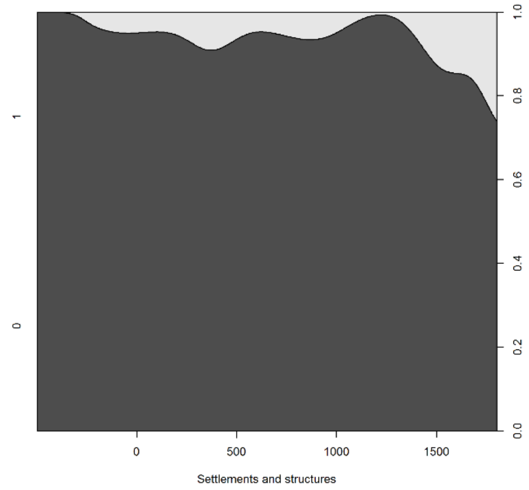

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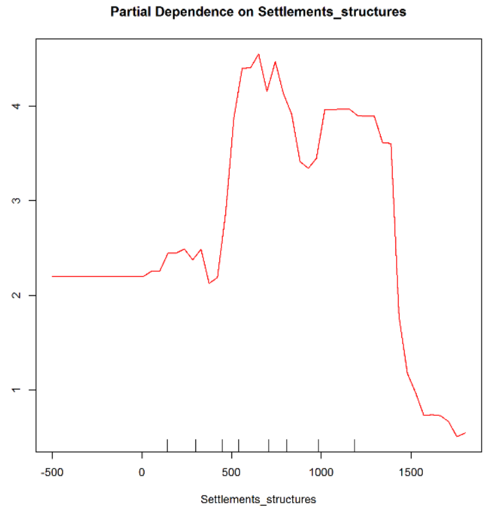

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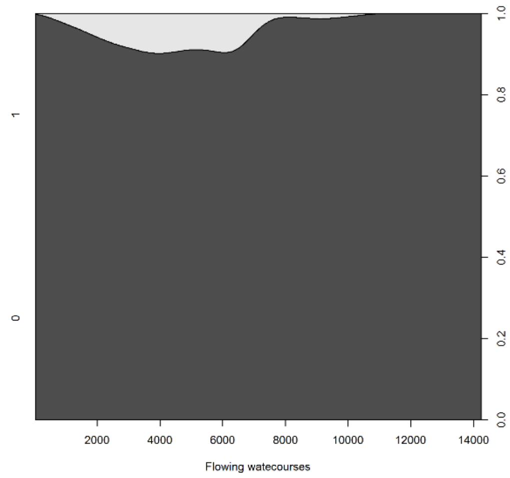

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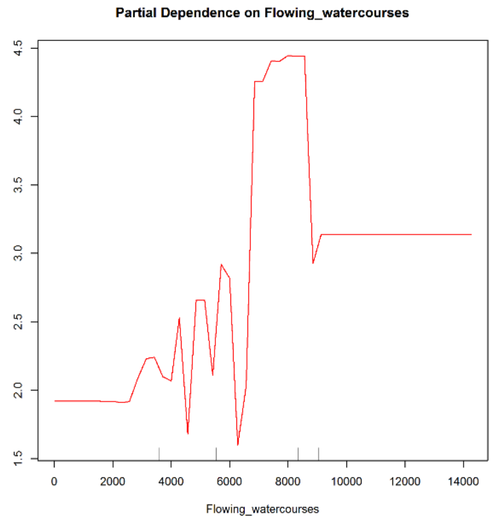

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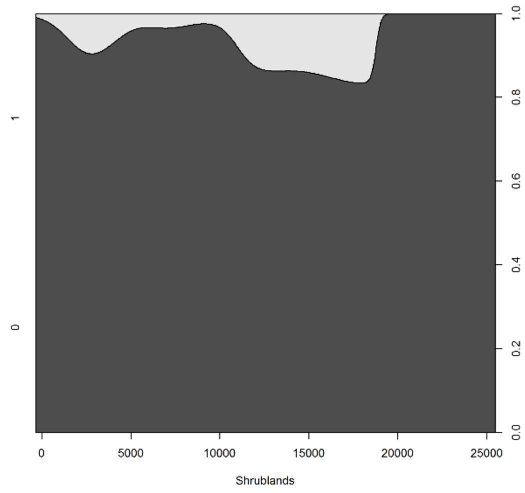

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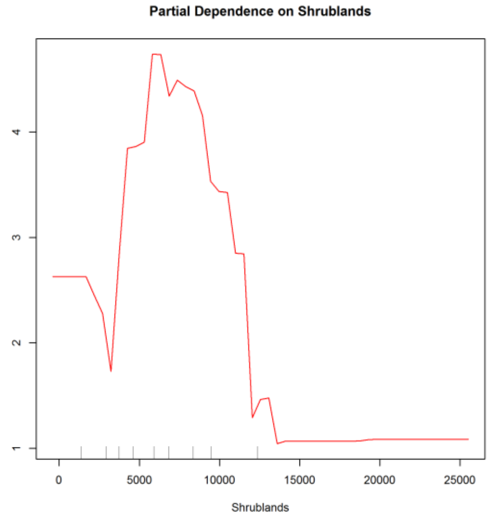

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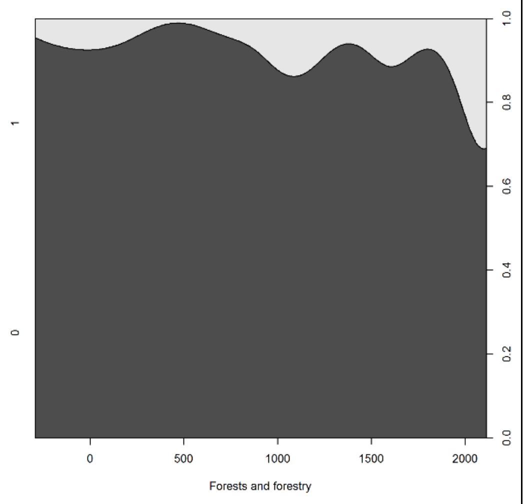

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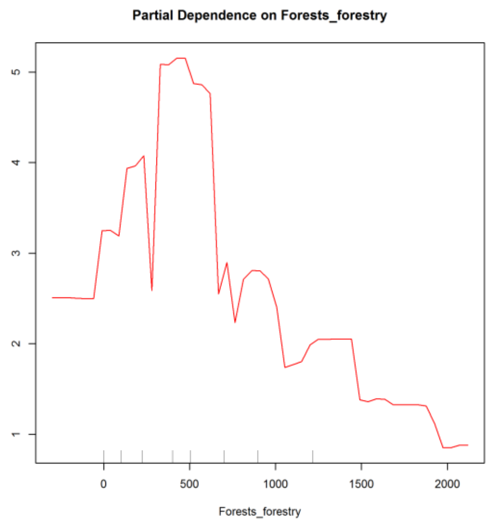

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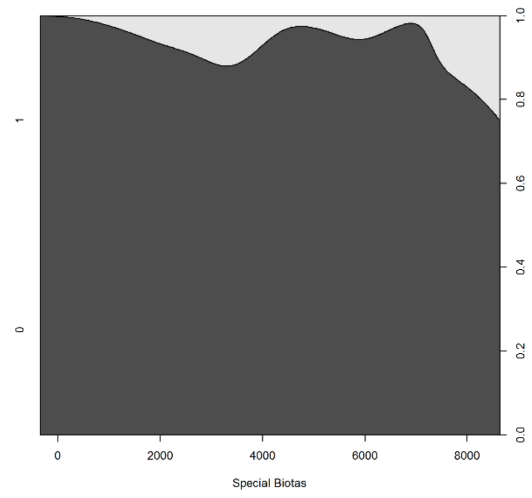

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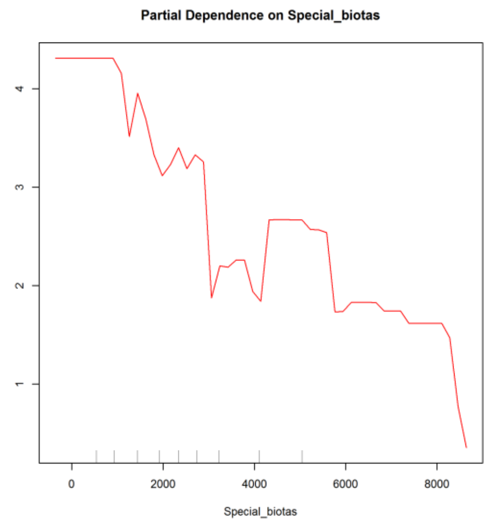

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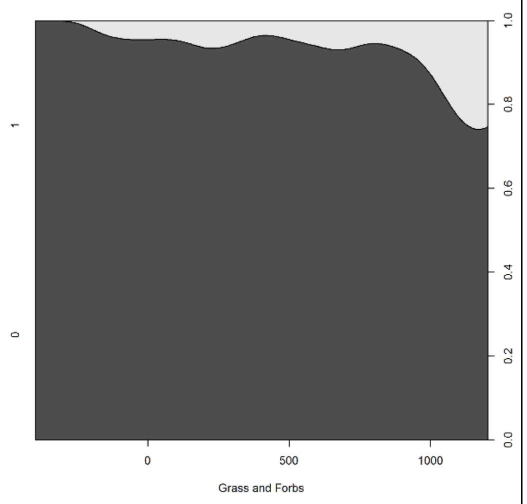

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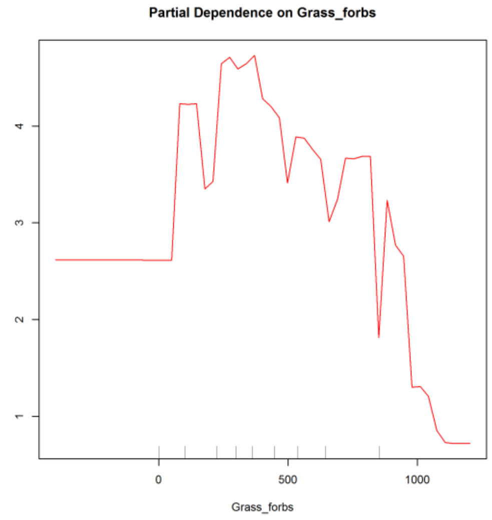

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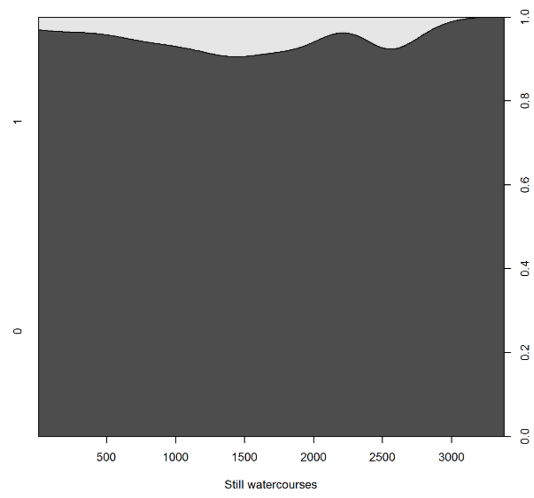

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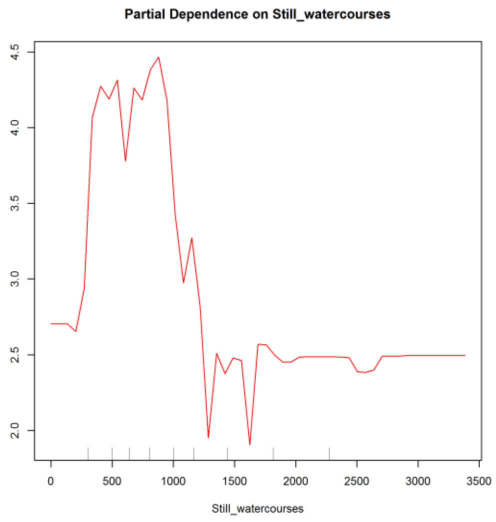

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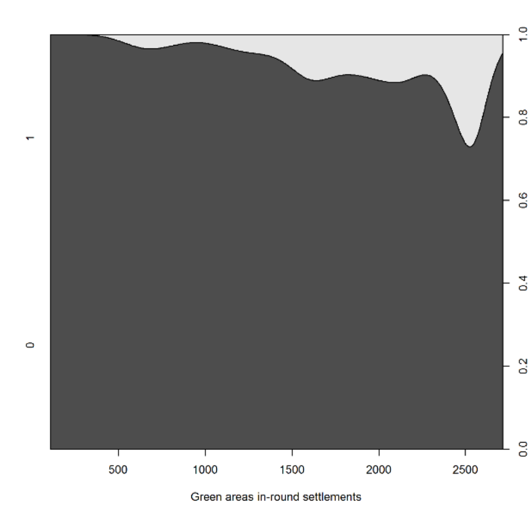

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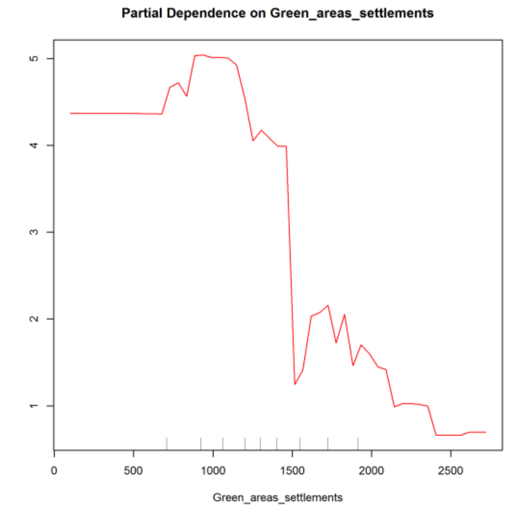

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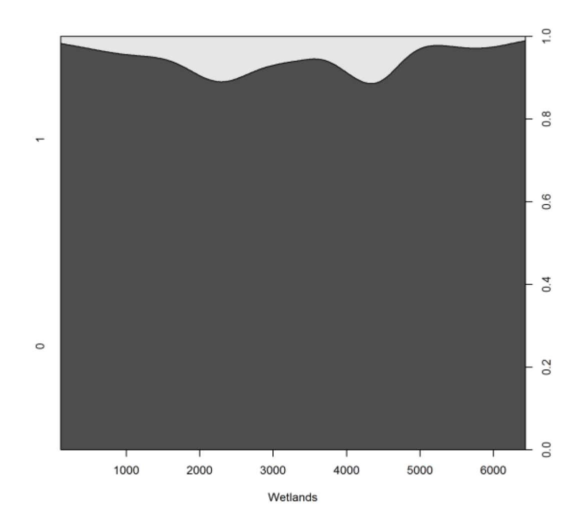

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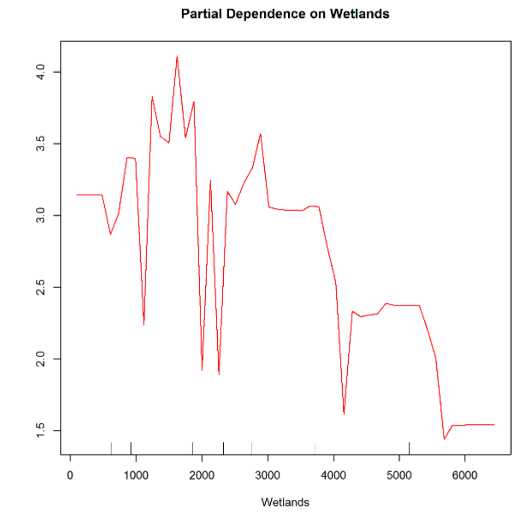
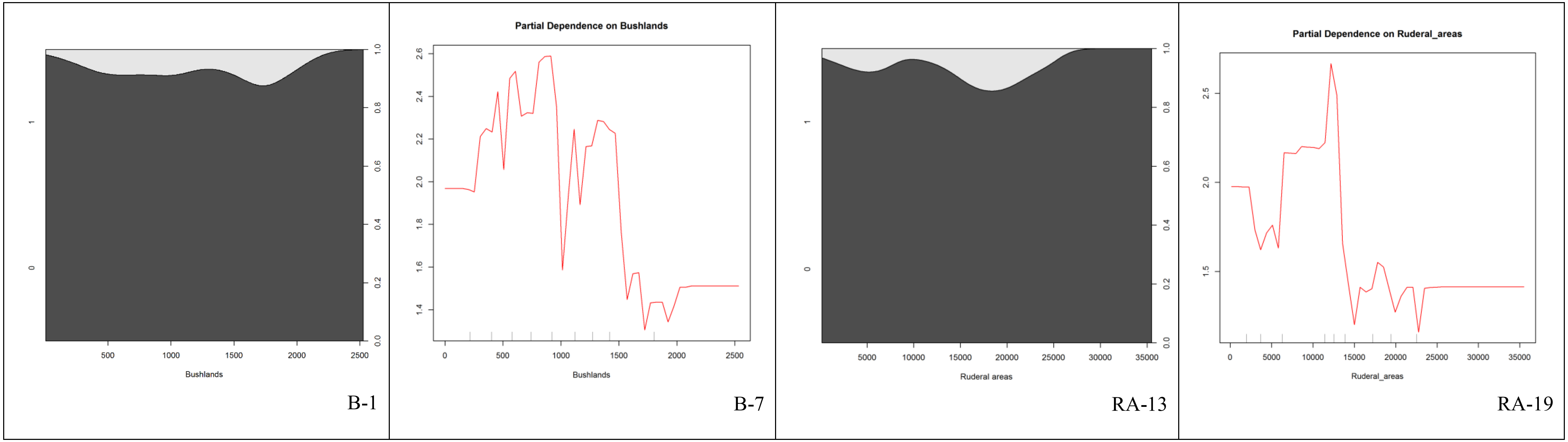
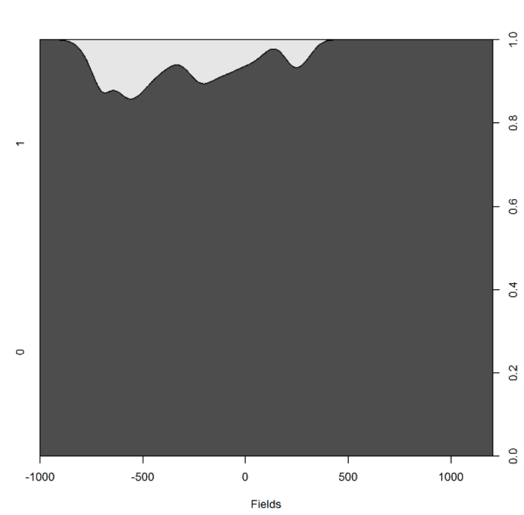


W-24

Annex: Figure A6: Exploration of the mechanistic relationships and interaction between Larks collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)





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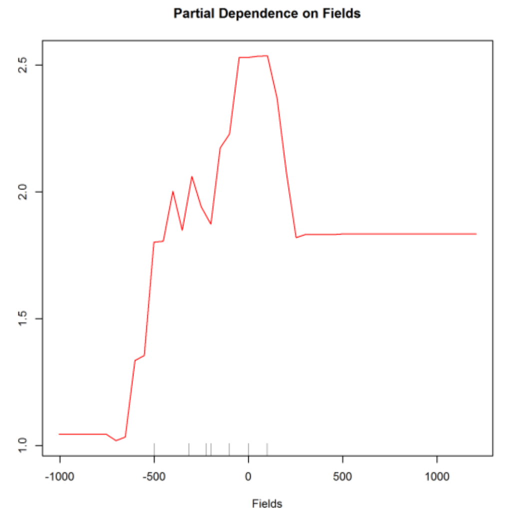

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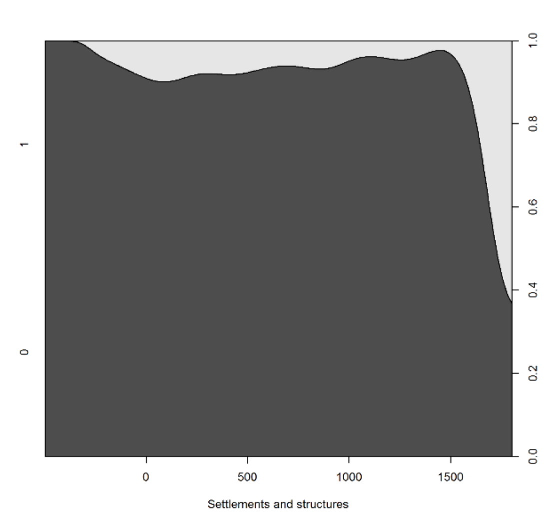

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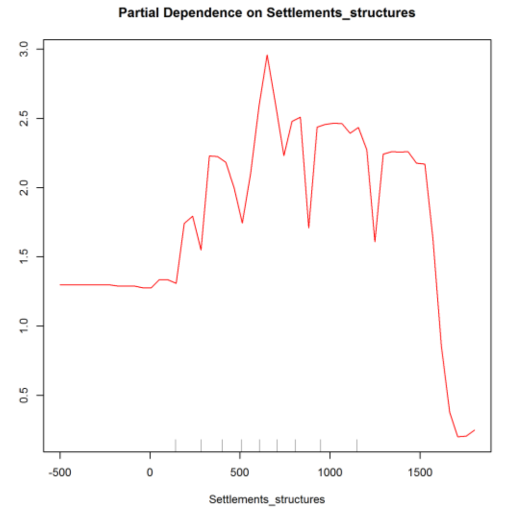

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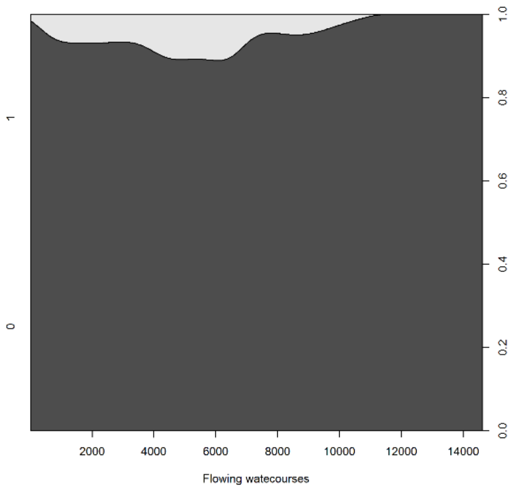

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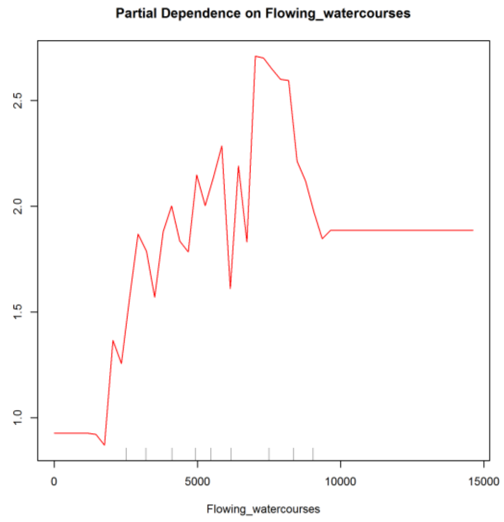

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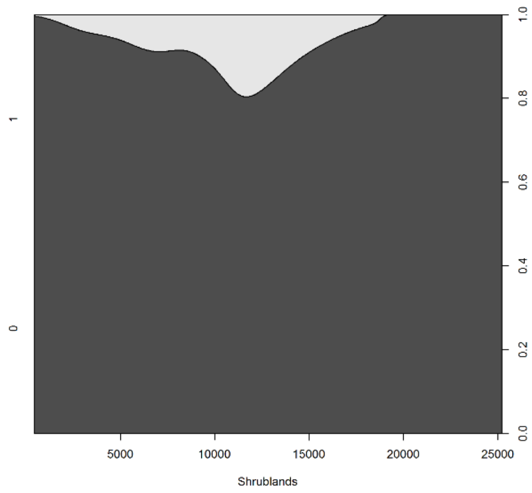

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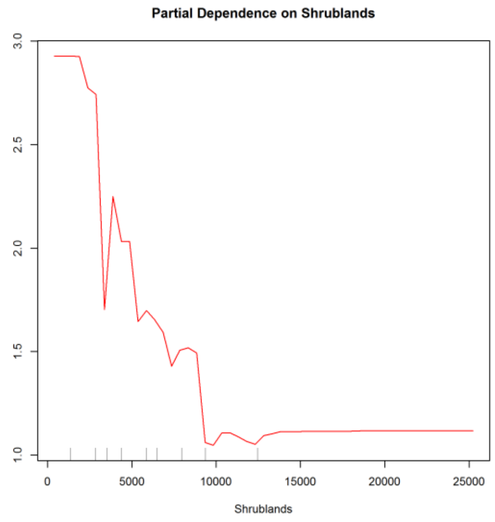

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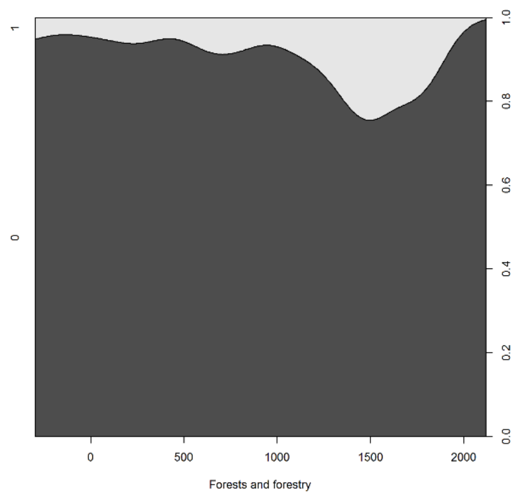

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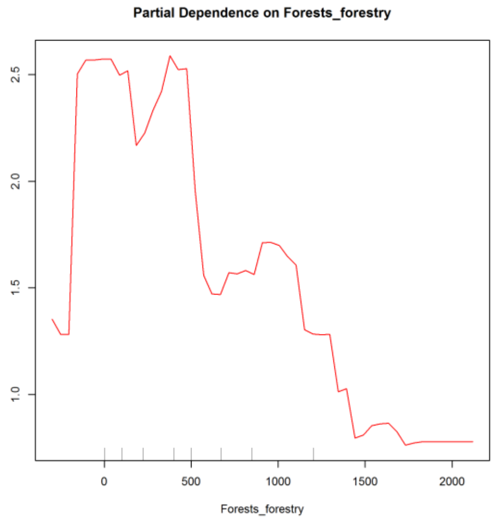

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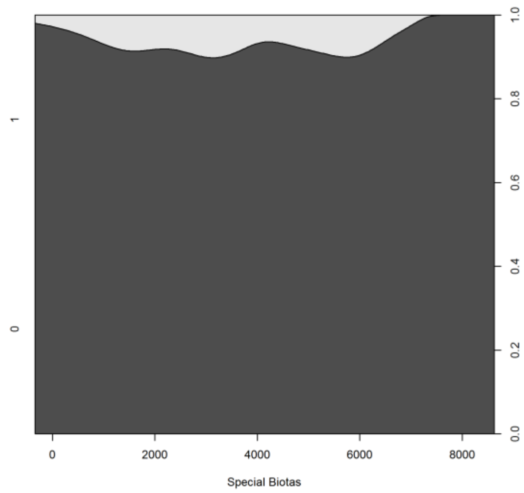

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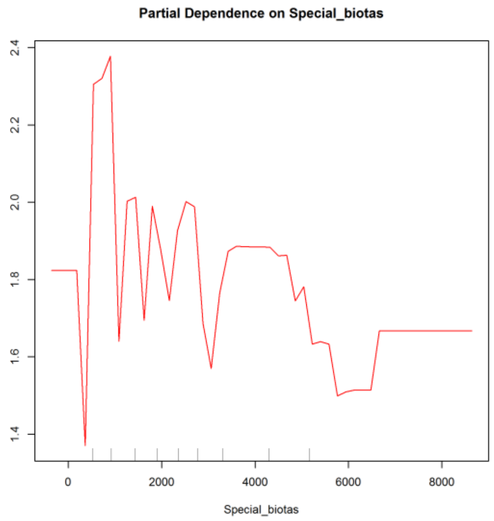

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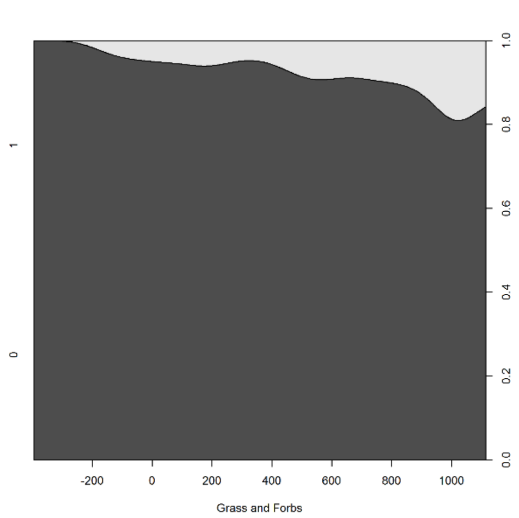

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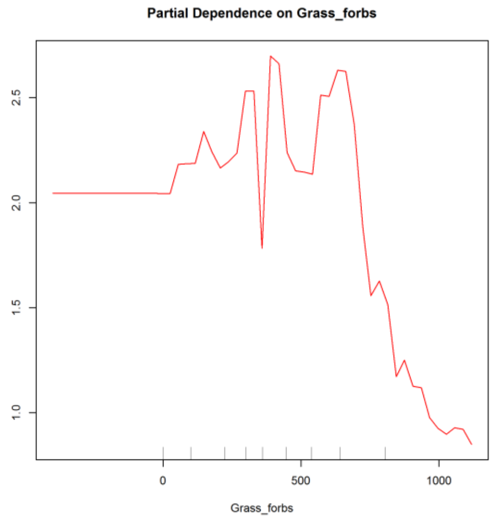

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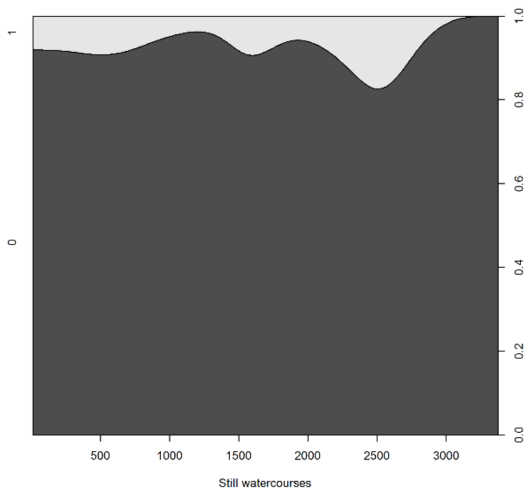

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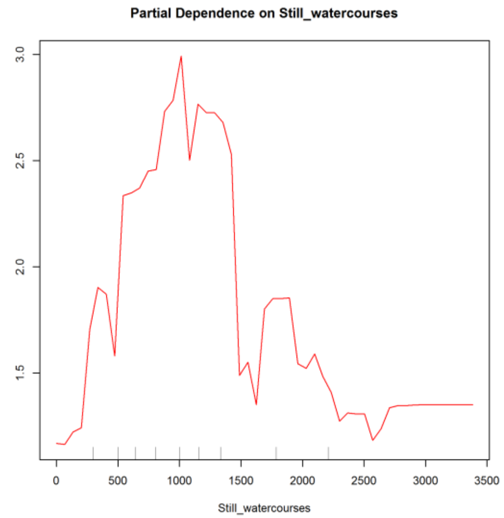

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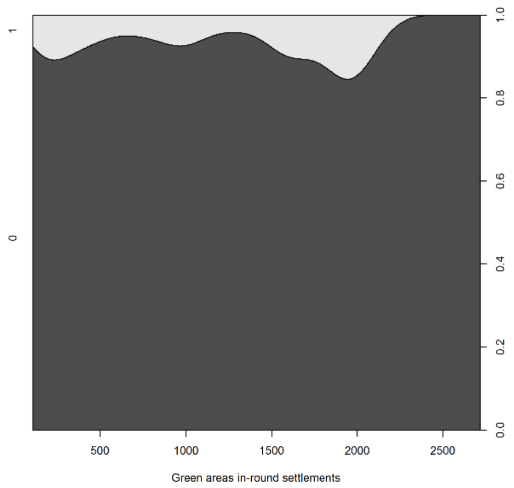

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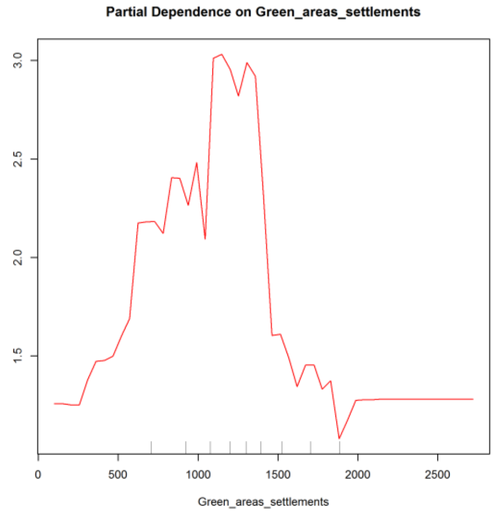

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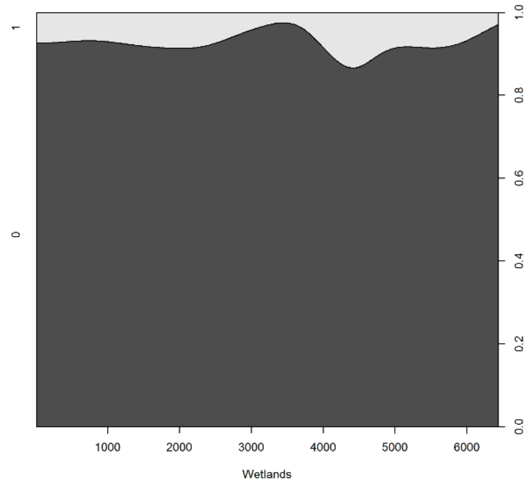

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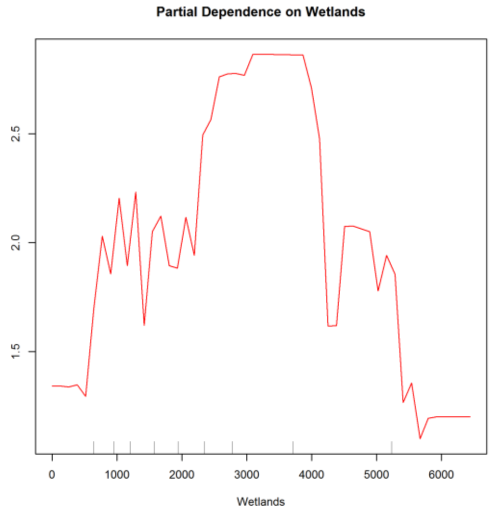
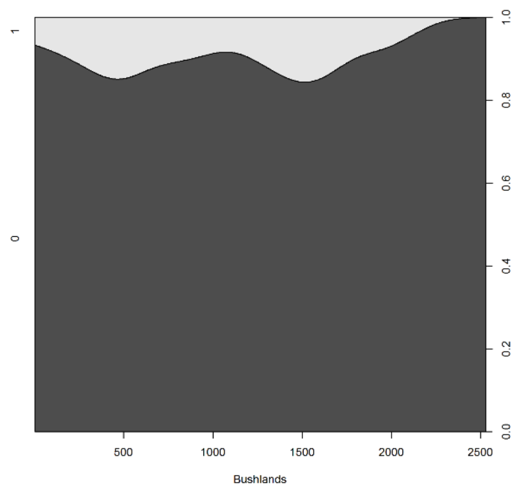


W-24

Annex: Figure A7: Exploration of the mechanistic relationships and interaction between Pigeons collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)



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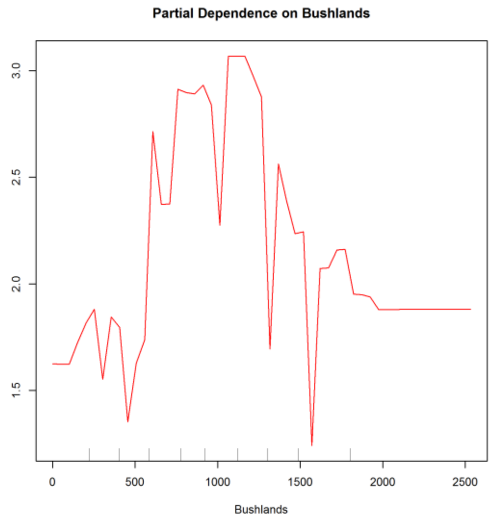
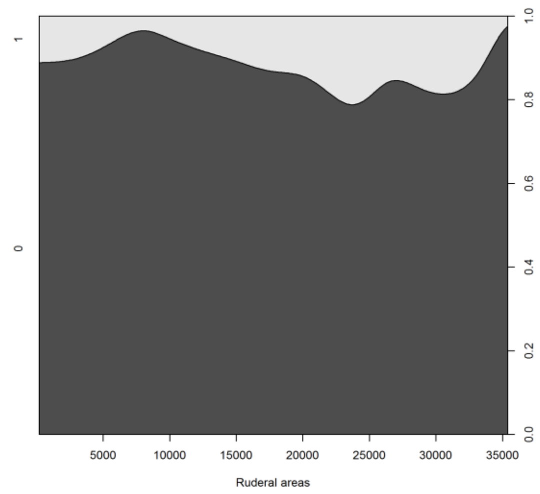


B-7



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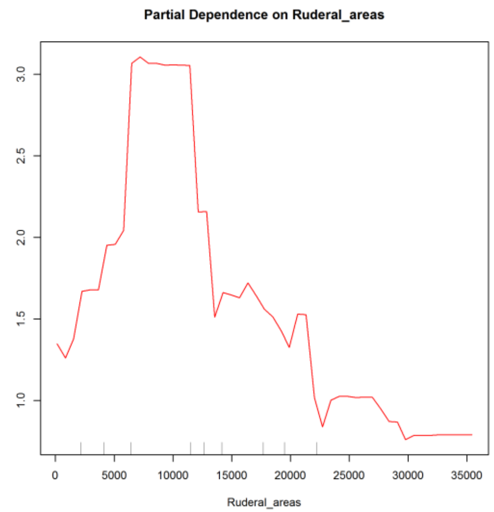

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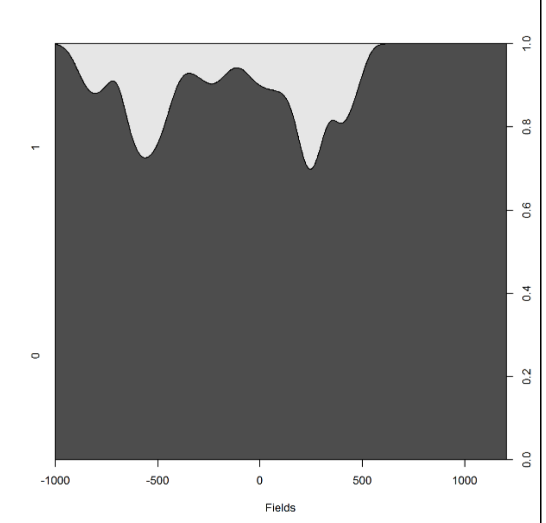

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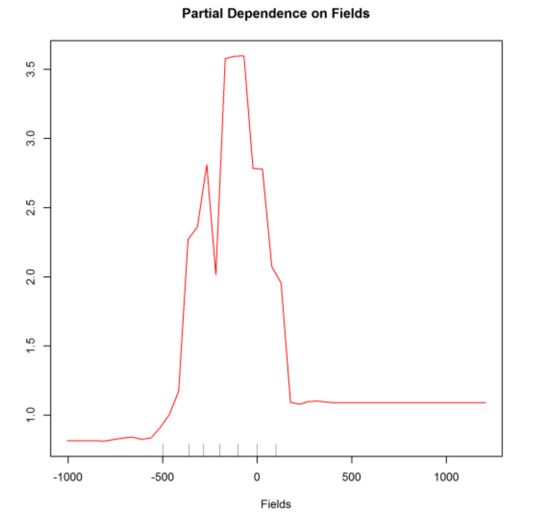

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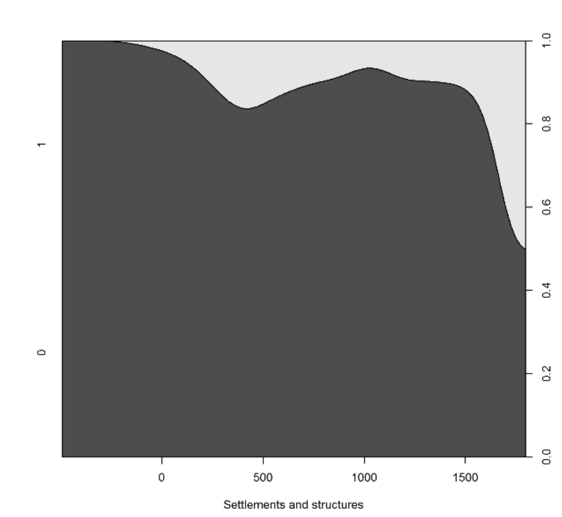

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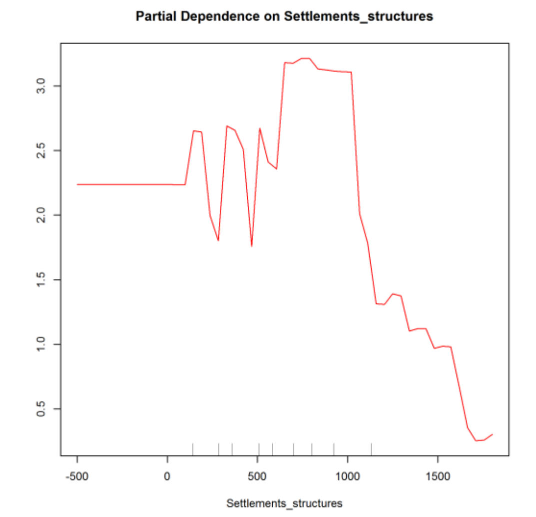

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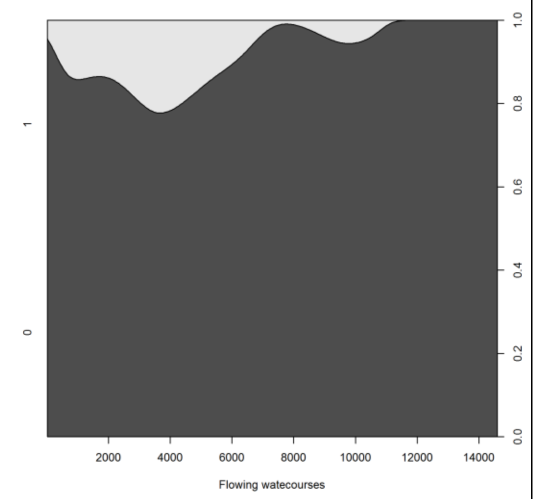

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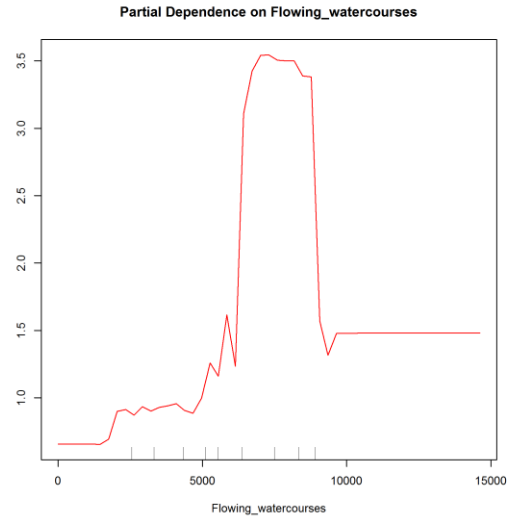

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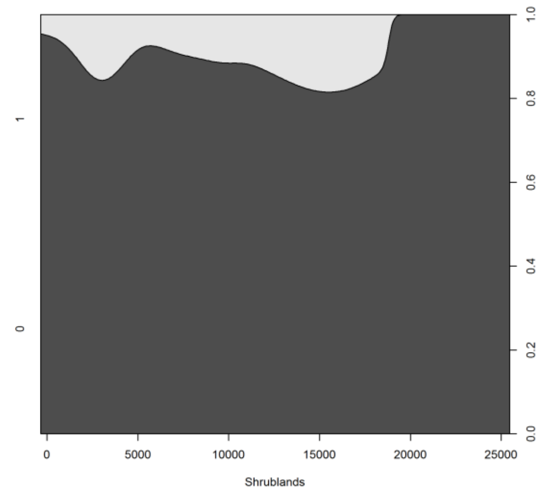

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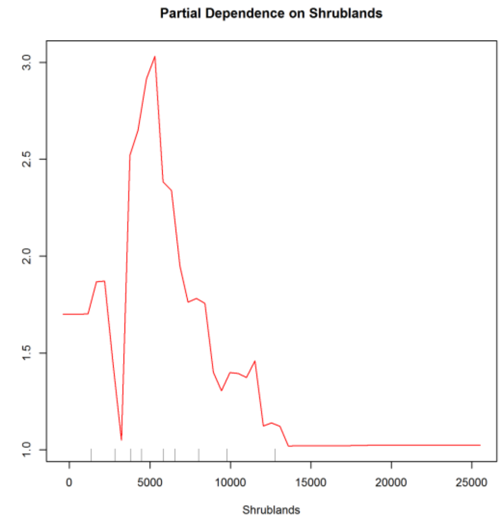

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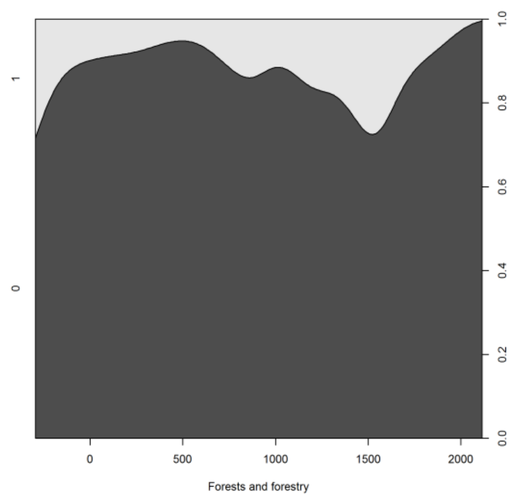

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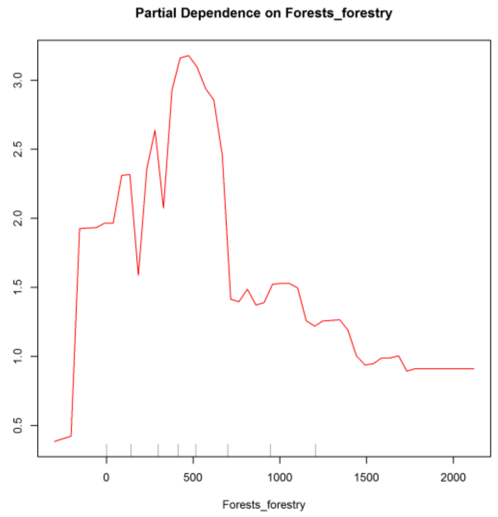

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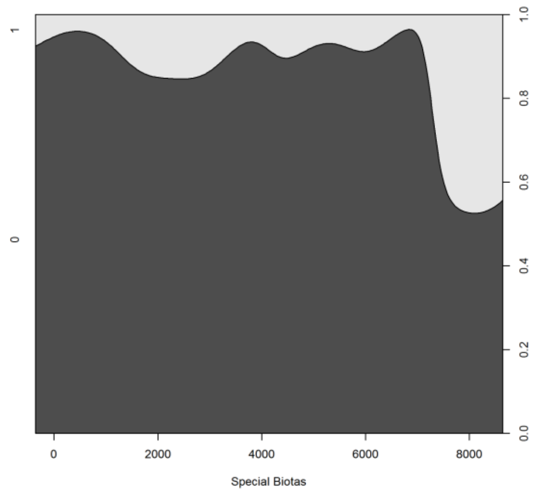

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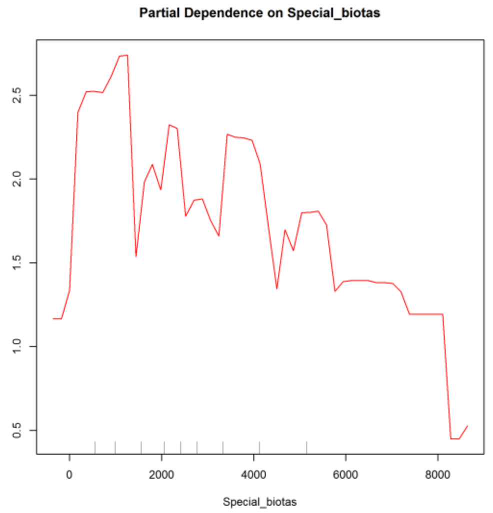

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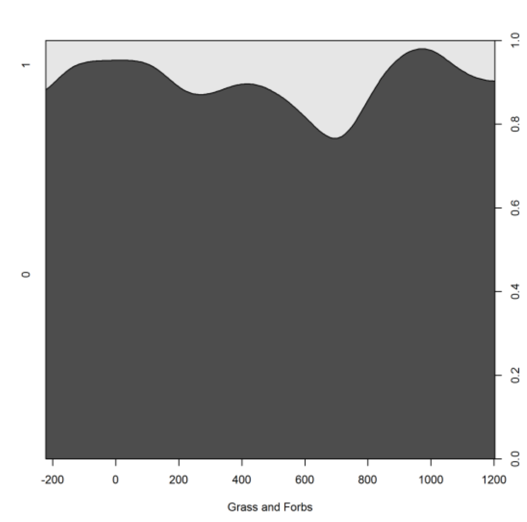

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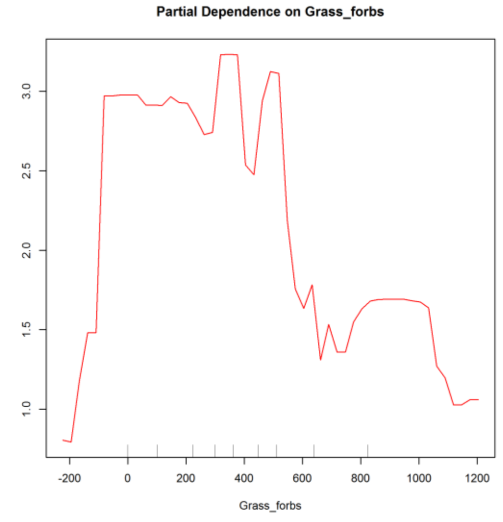

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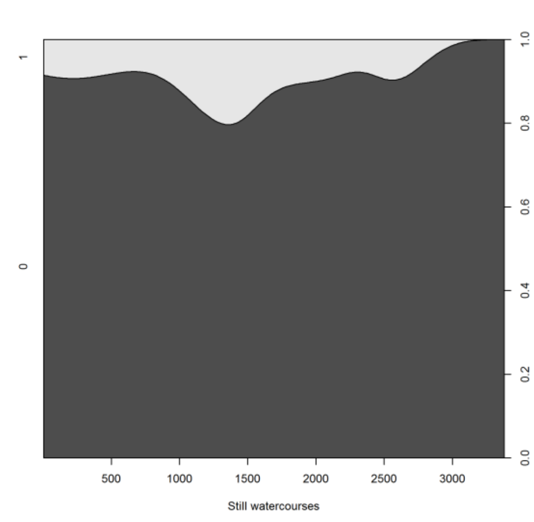

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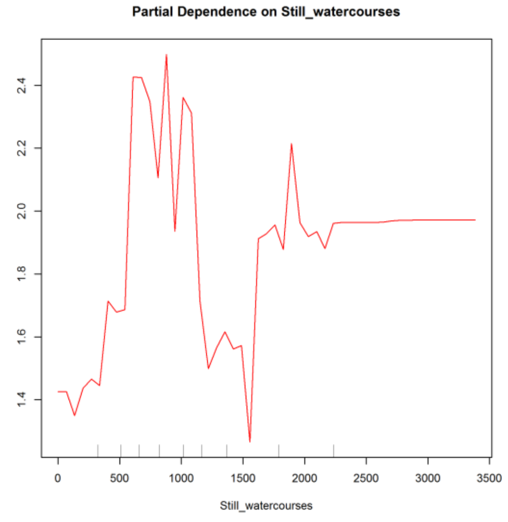

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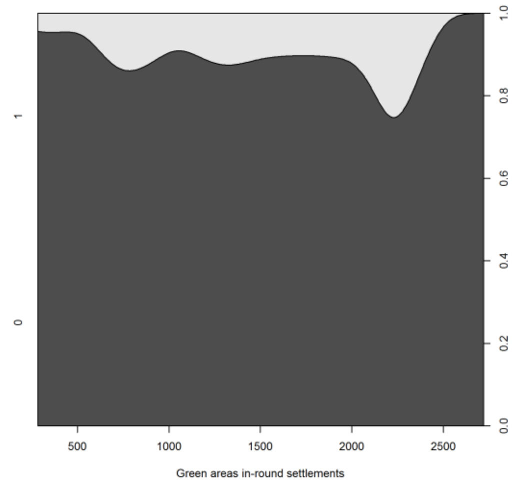

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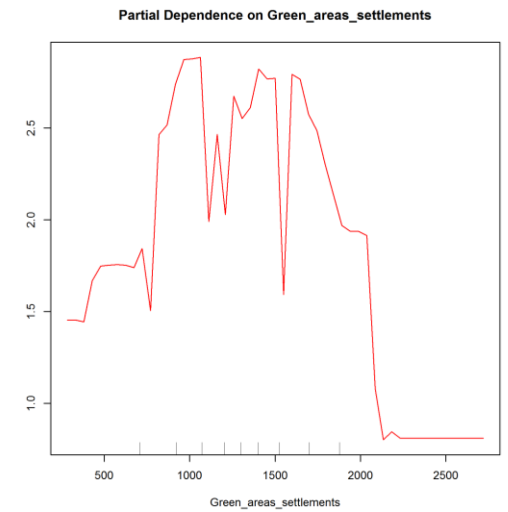

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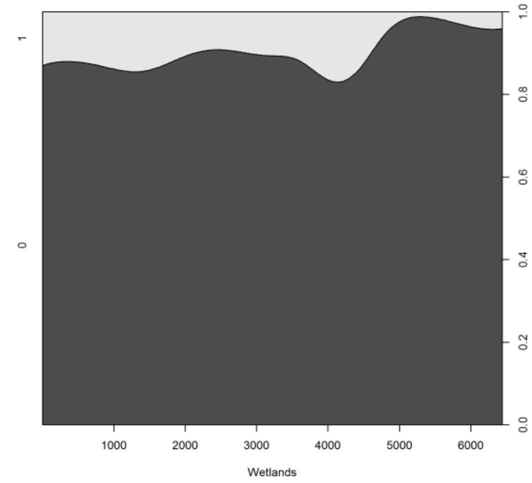

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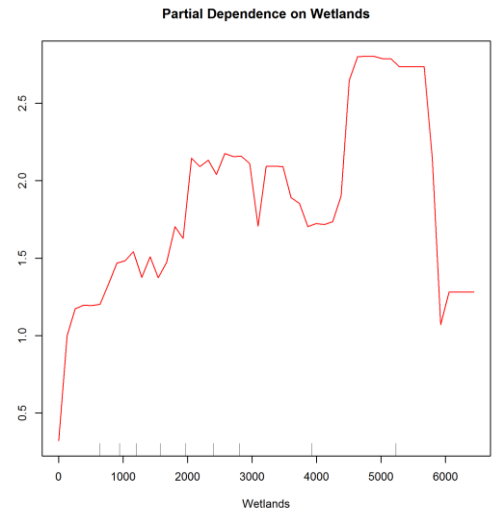
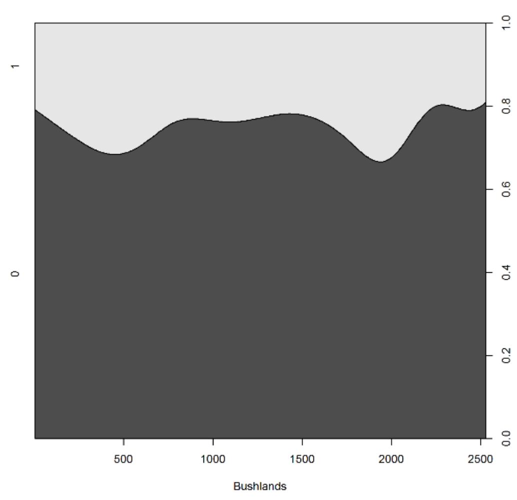


W-24

Annex: Figure A8: Exploration of the mechanistic relationships and interaction between Raptors collision response and DELVs at the WTs in the federal state of Brandenburg (a) Conditional density plot of DELVs: presence/absence of the detected collisions (1-6, 13-18) and (b) Partial plot of DELVs: Possibility of collisions simulated by RF (7-12, 19-24)



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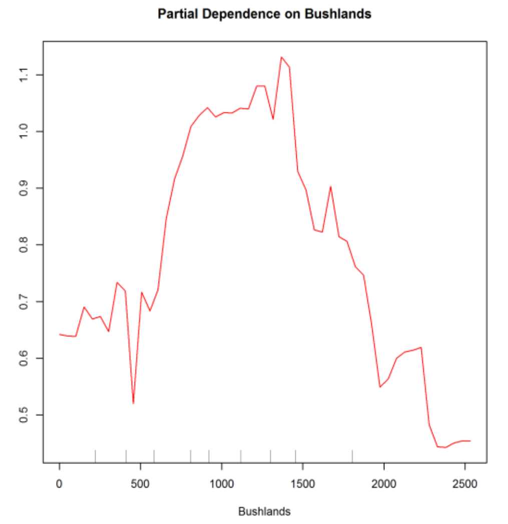

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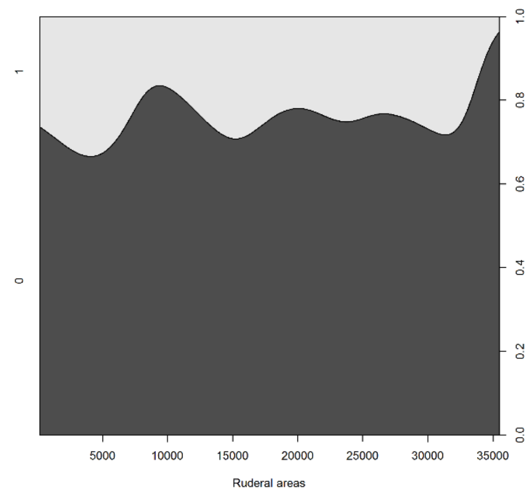
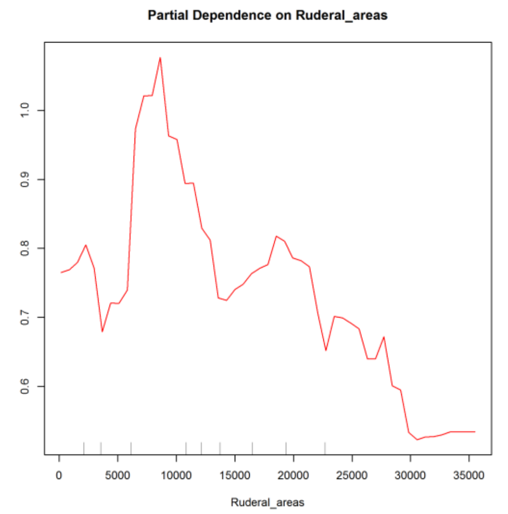


RA-13



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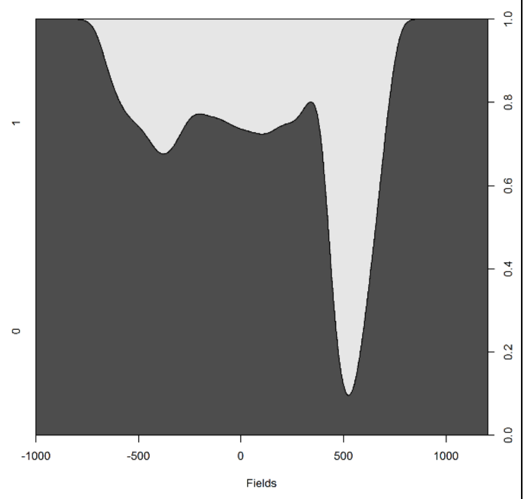

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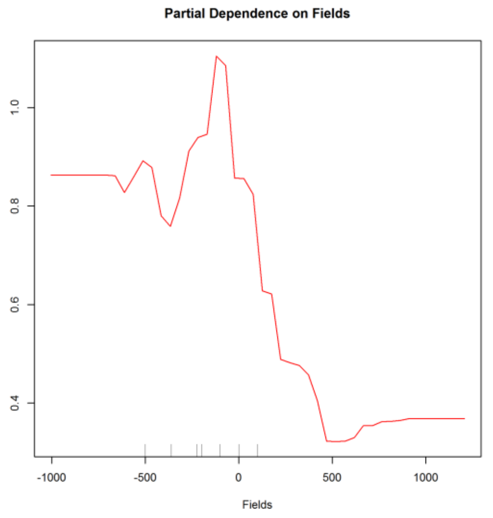

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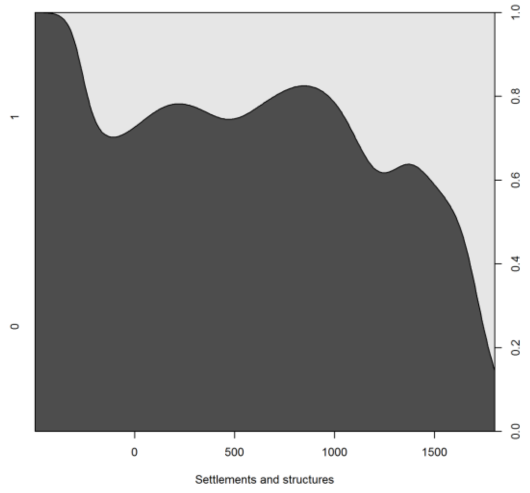

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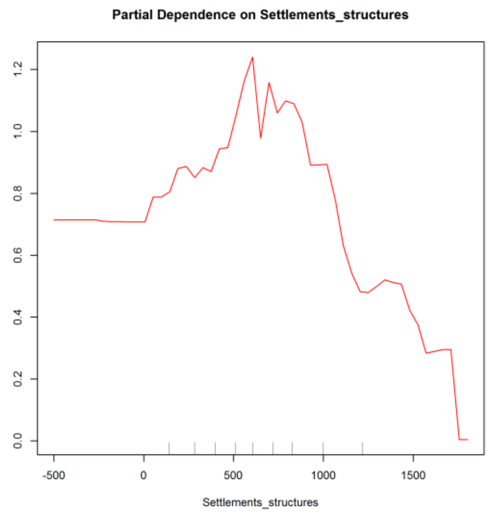

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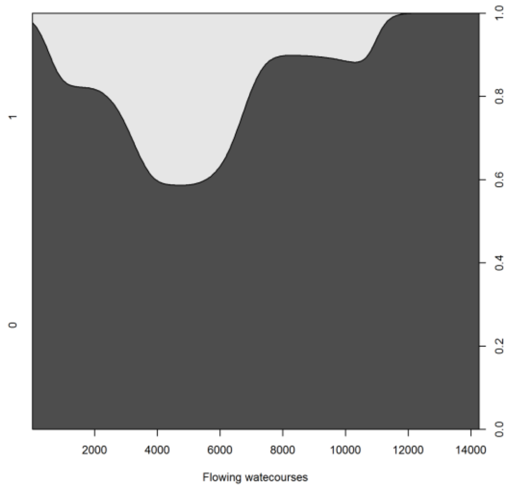
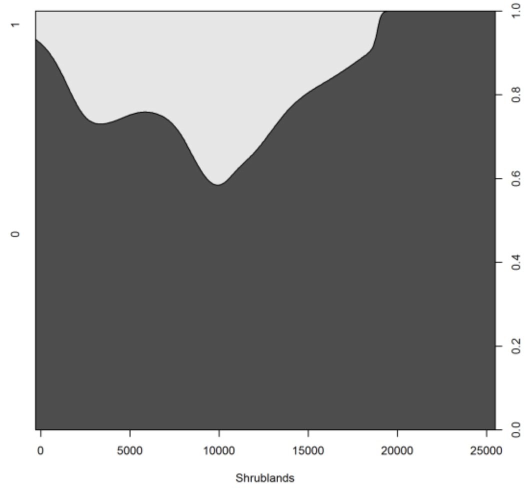


FW-3

FW-9



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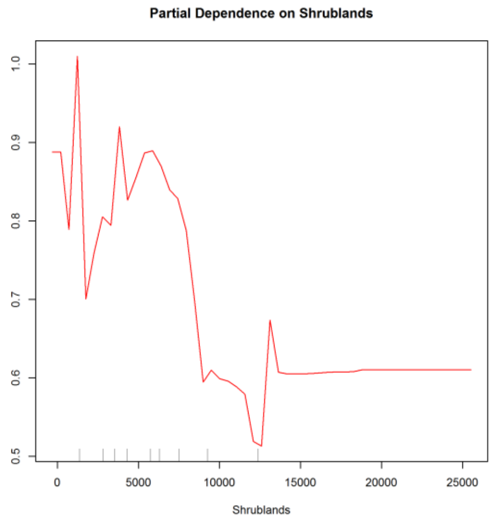

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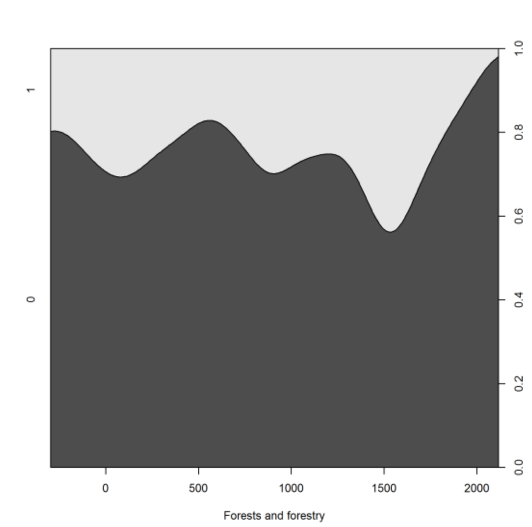

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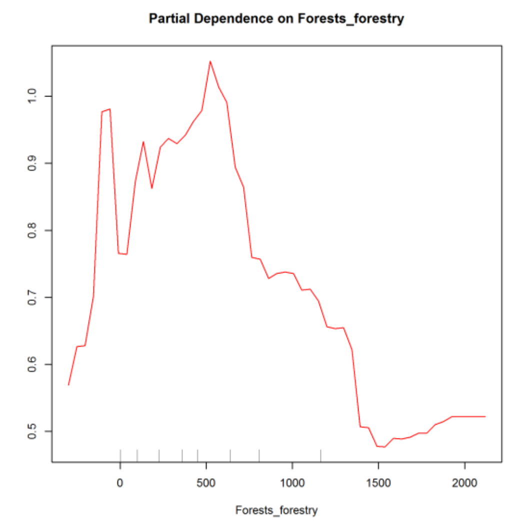

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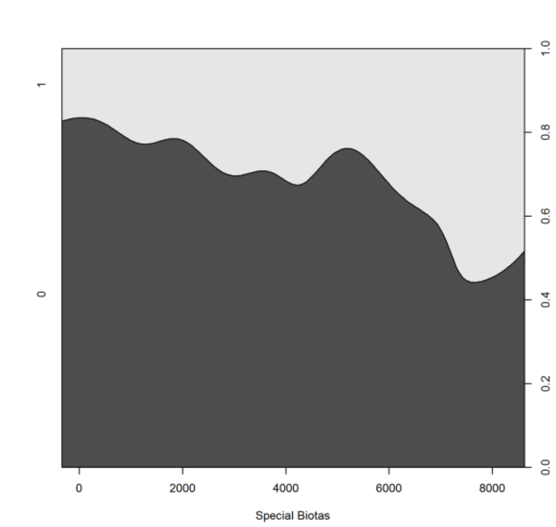

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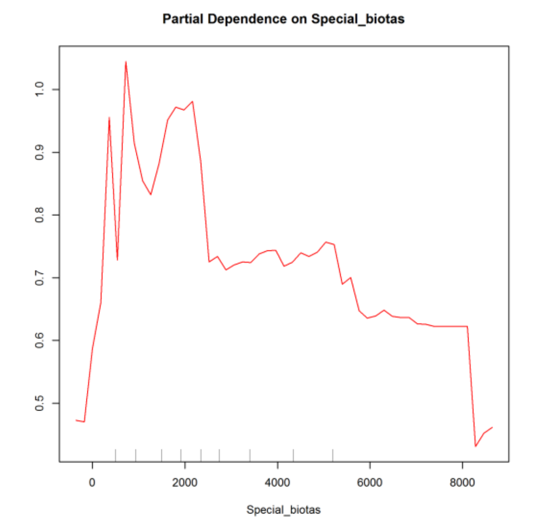

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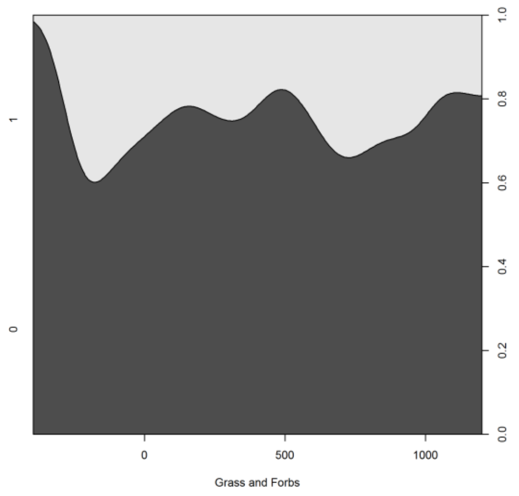

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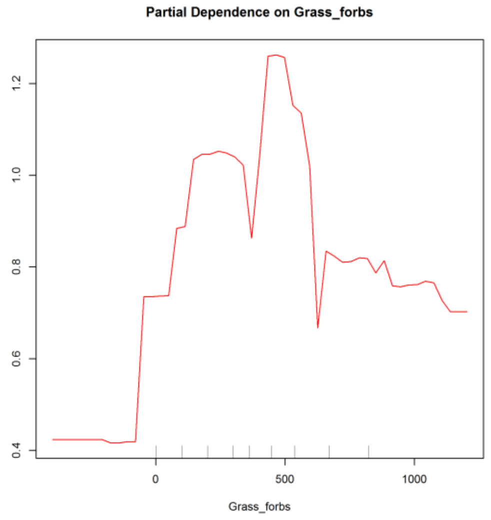

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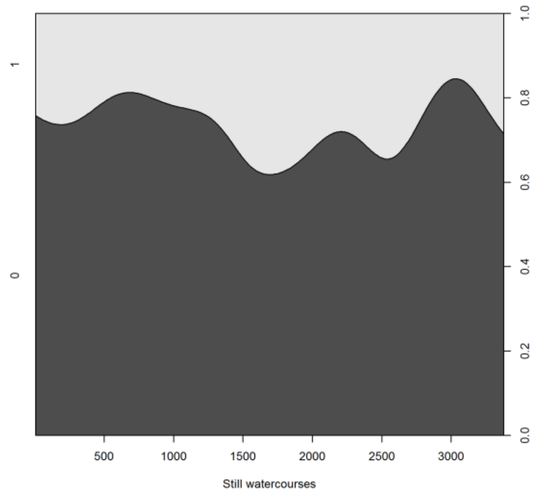

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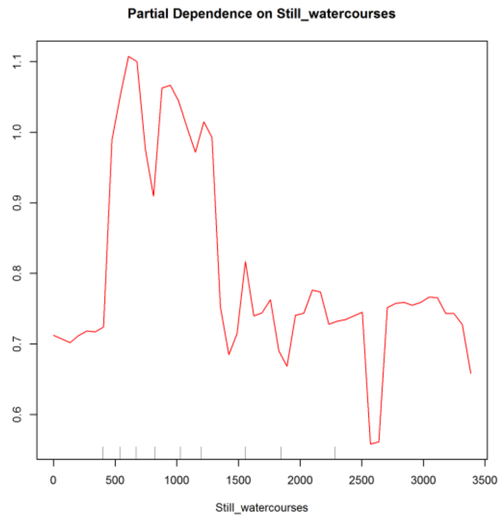

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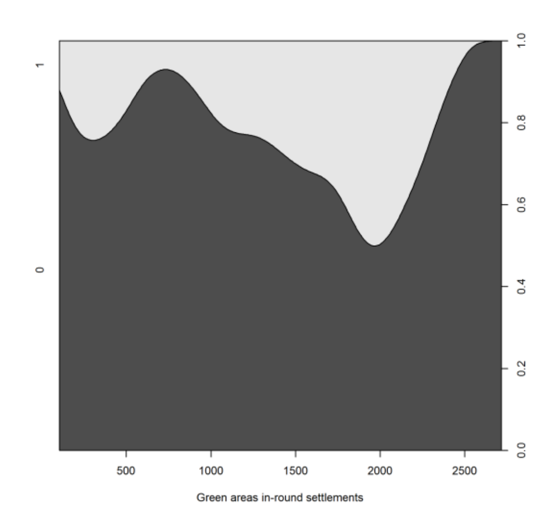

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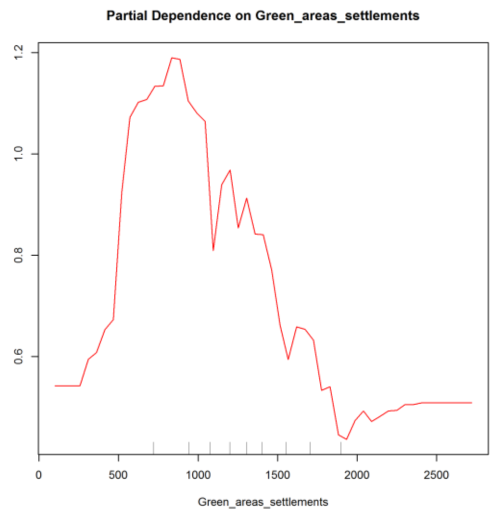

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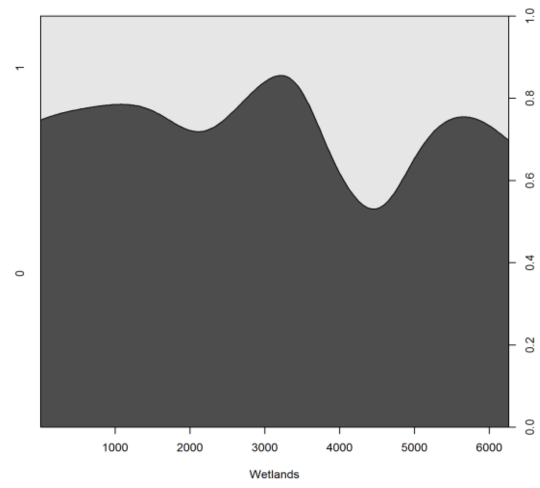

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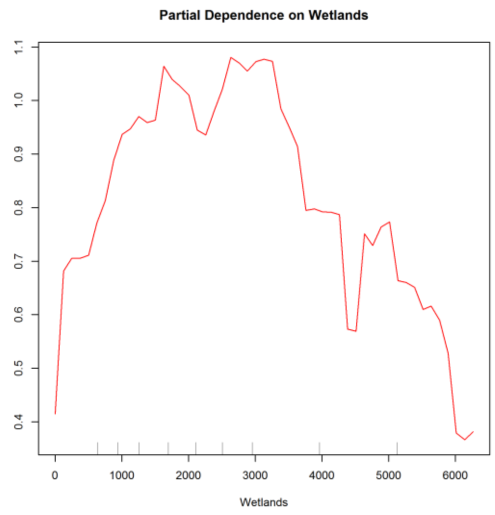
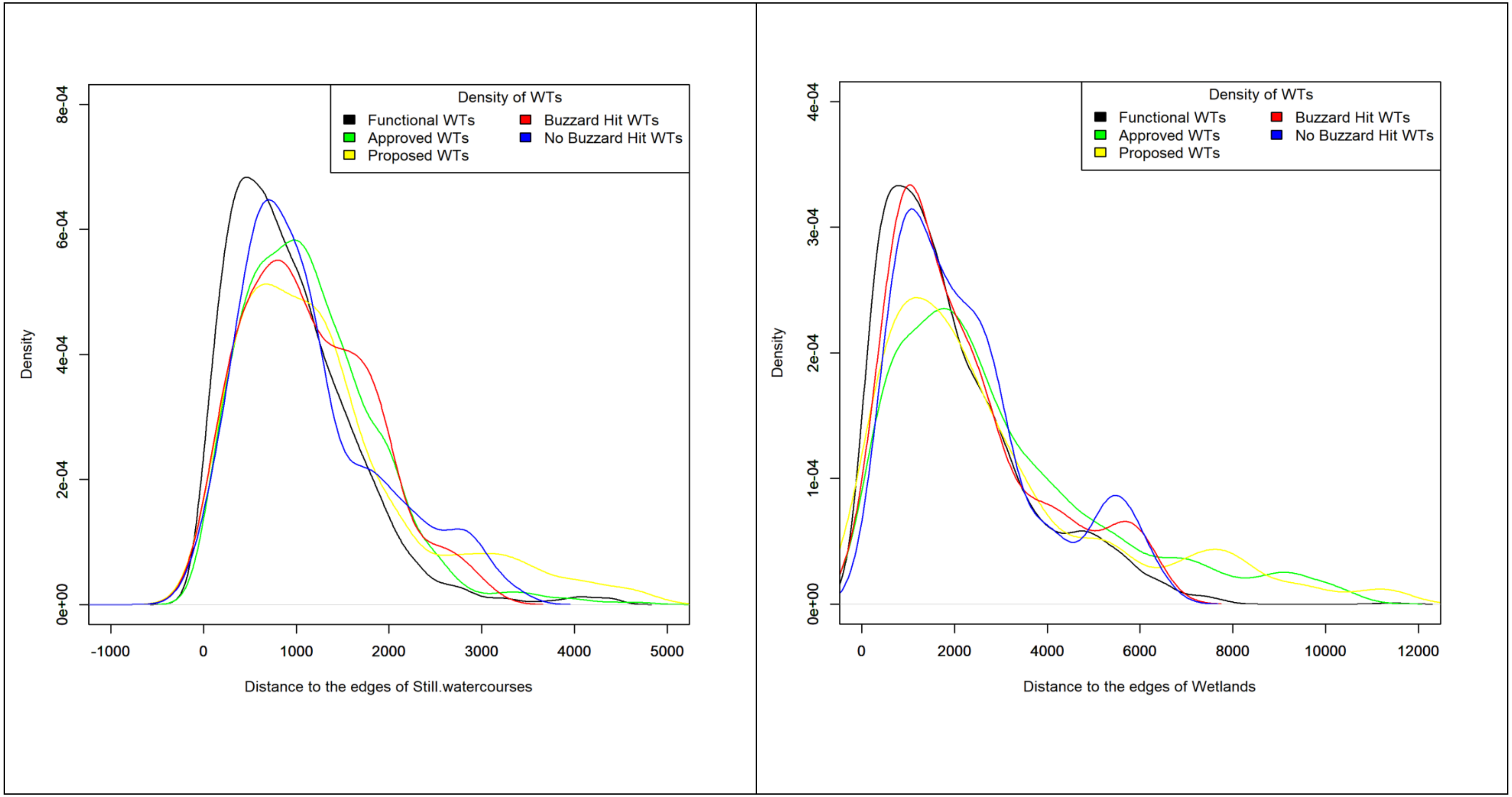
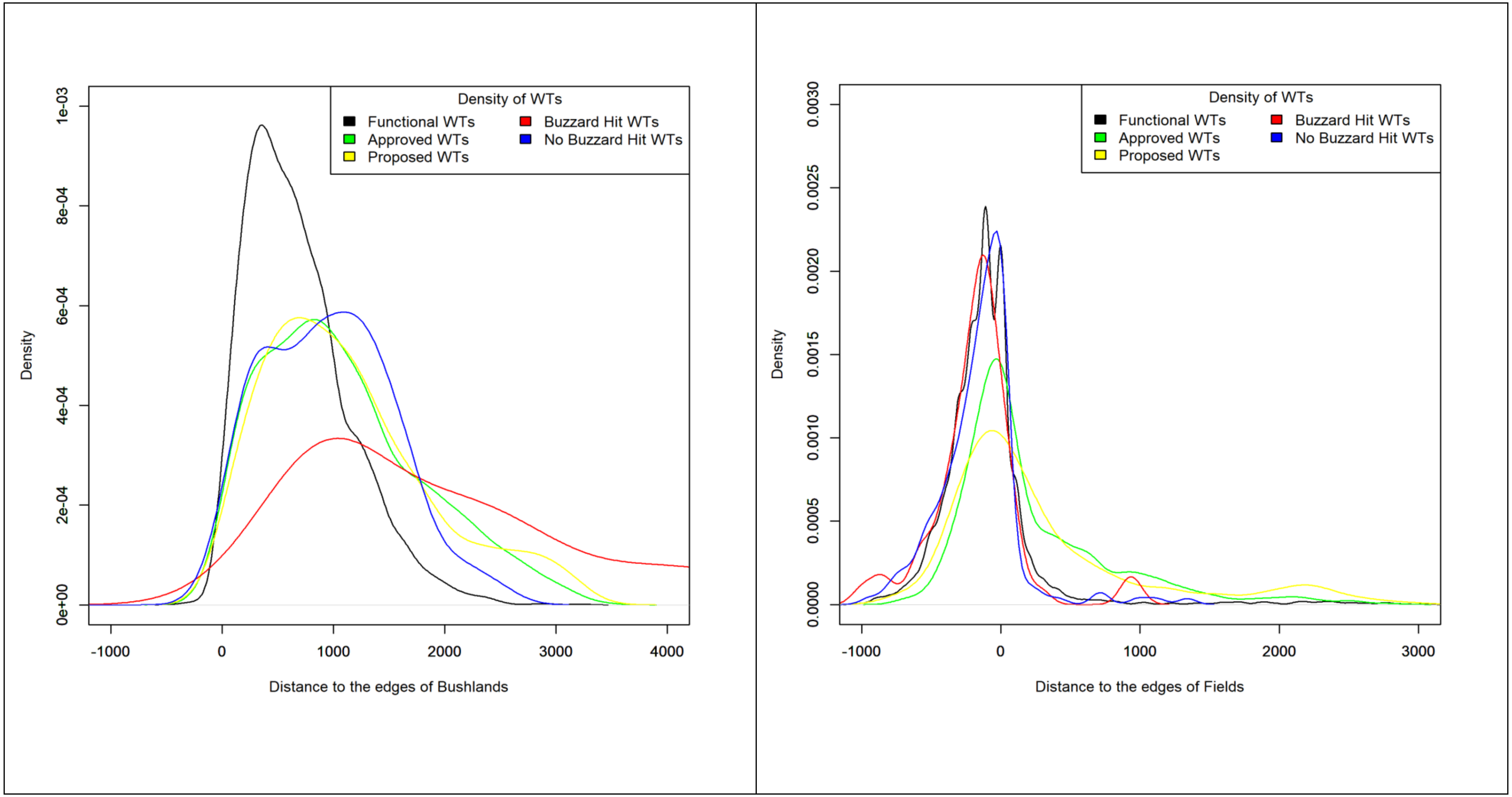


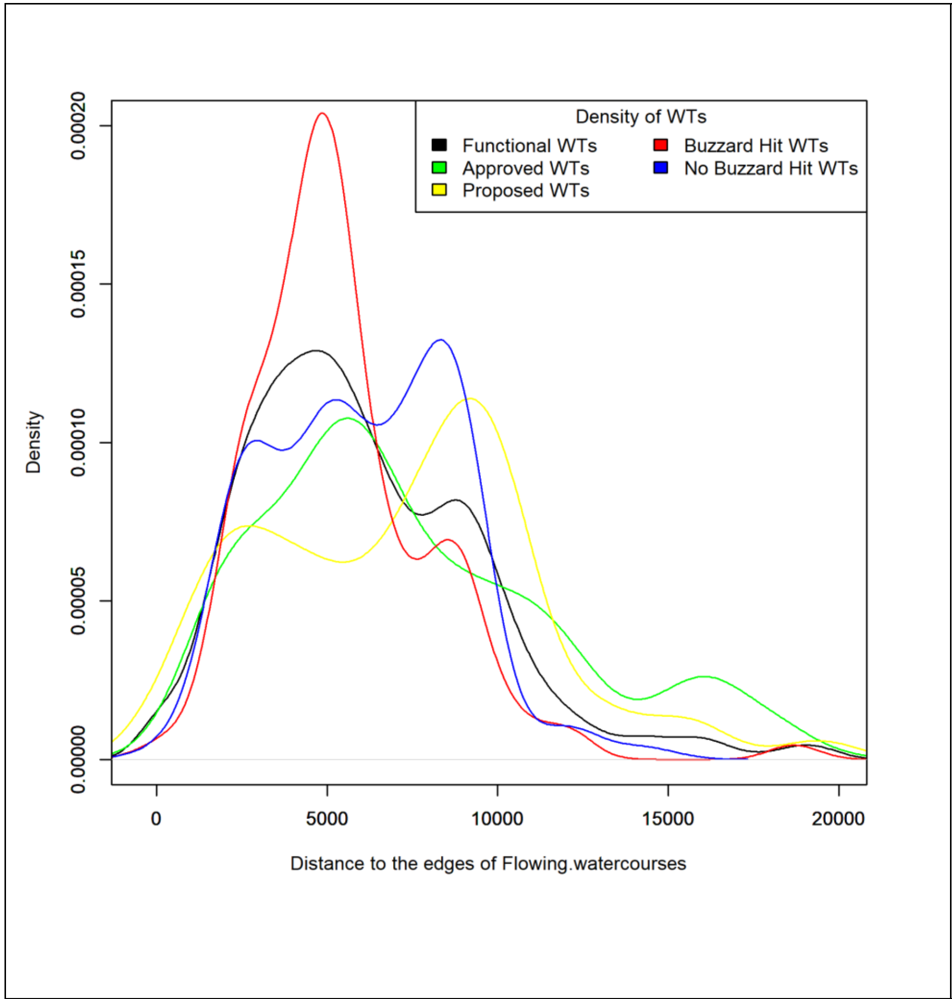
W-24

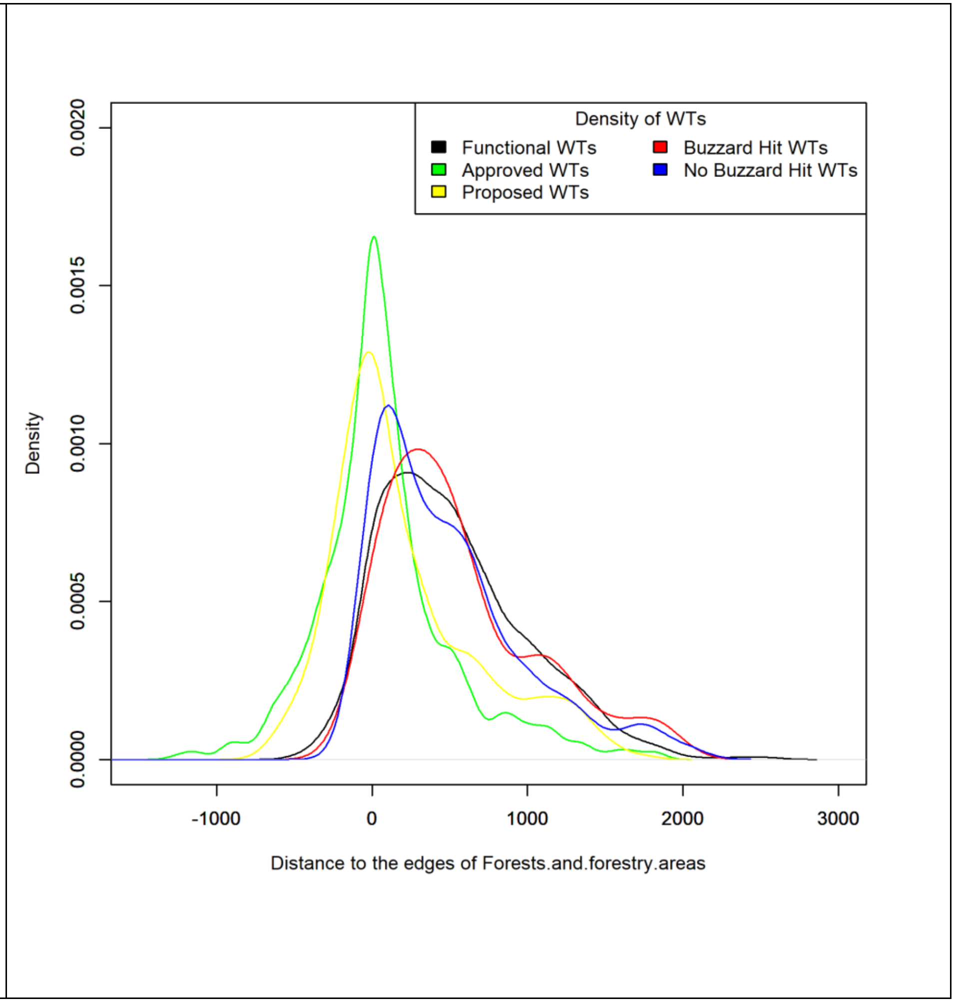
Annex: Figure A9: Distance distributions to different land-use types; of turbines under the functional, approved and proposed categories respectively, of the Ministry of Environment, Health and Consumer Protection for the state of Brandenburg (LUGV 2014).





Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0e+00
2e-04
4e-04
6e-04
8e-04
1e-03
-1000
0
1000
2000
3000
4000
Distance to the edges of Bushlands
Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
-1000
0
1000
2000
3000
Distance to the edges of Fields


Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.00000
0.00005
0.00010
0.00015
0.00020
0
5000
10000
15000
20000
Distance to the edges of Flowing.watercourses


Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
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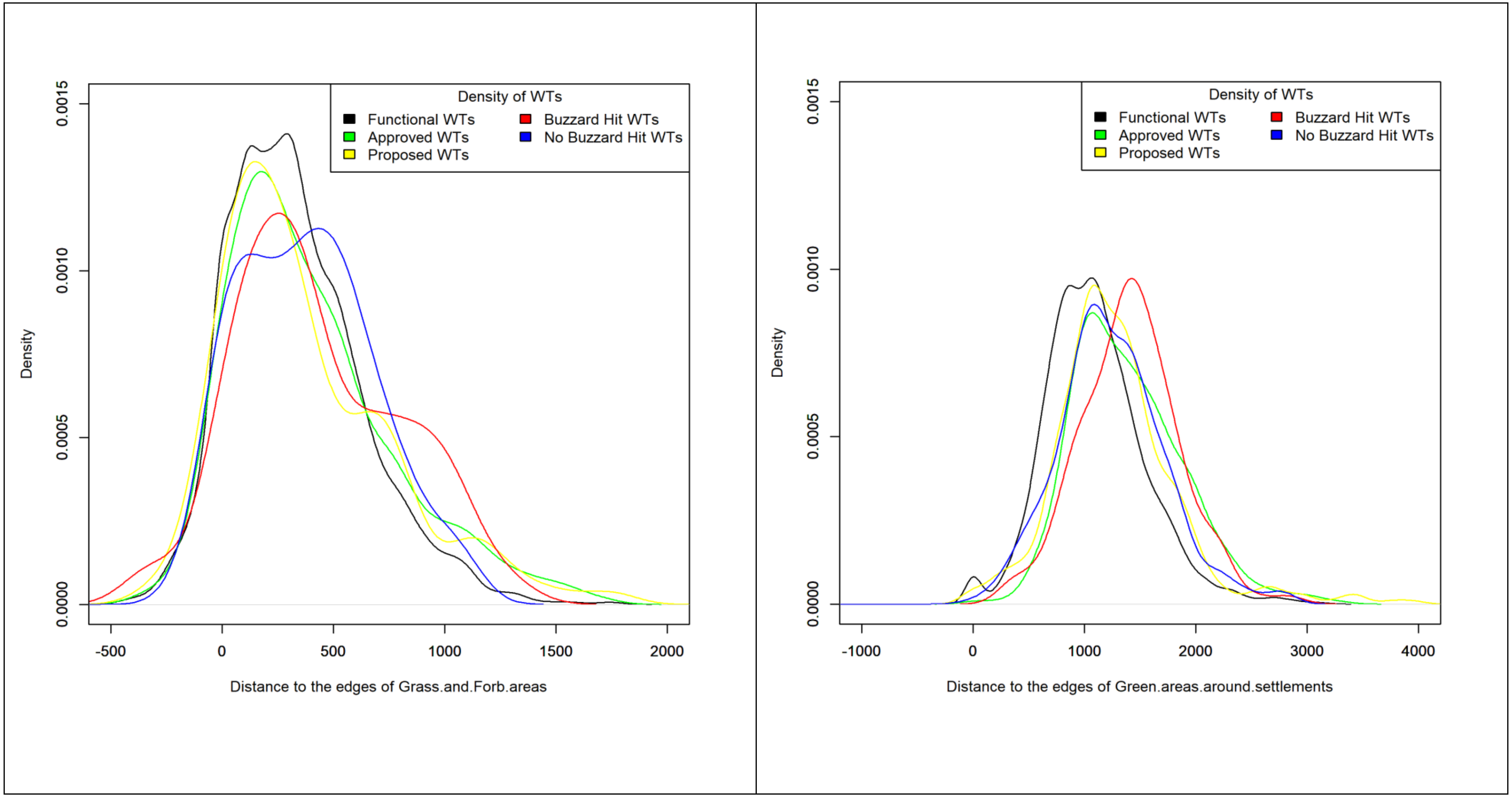
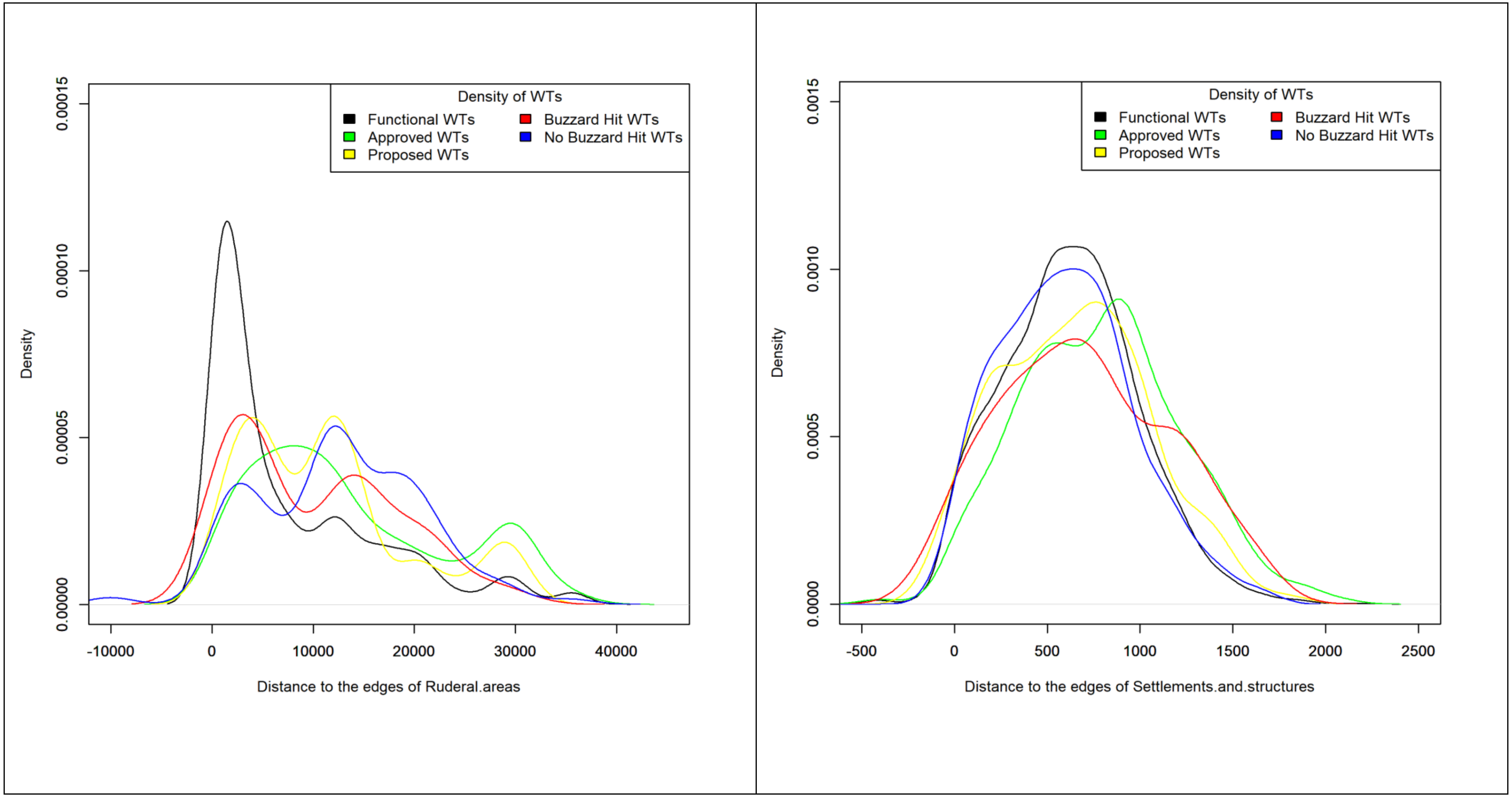
0.0010
0.0015
0.0020
-1000
0
1000
2000
3000
Distance to the edges of Forests.and.forestry.areas


Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.0000
0.0005
0.0010
0.0015
-500
0
500
1000
1500
2000
Distance to the edges of Grass.and.Forb.areas
Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.0000
0.0005
0.0010
0.0015
-1000
0
1000
2000
3000
4000
Distance to the edges of Green.areas.around.settlements


Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.00000
0.00005
0.00010
0.00015
-10000
0
10000
20000
30000
40000
Distance to the edges of Ruderal.areas
Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
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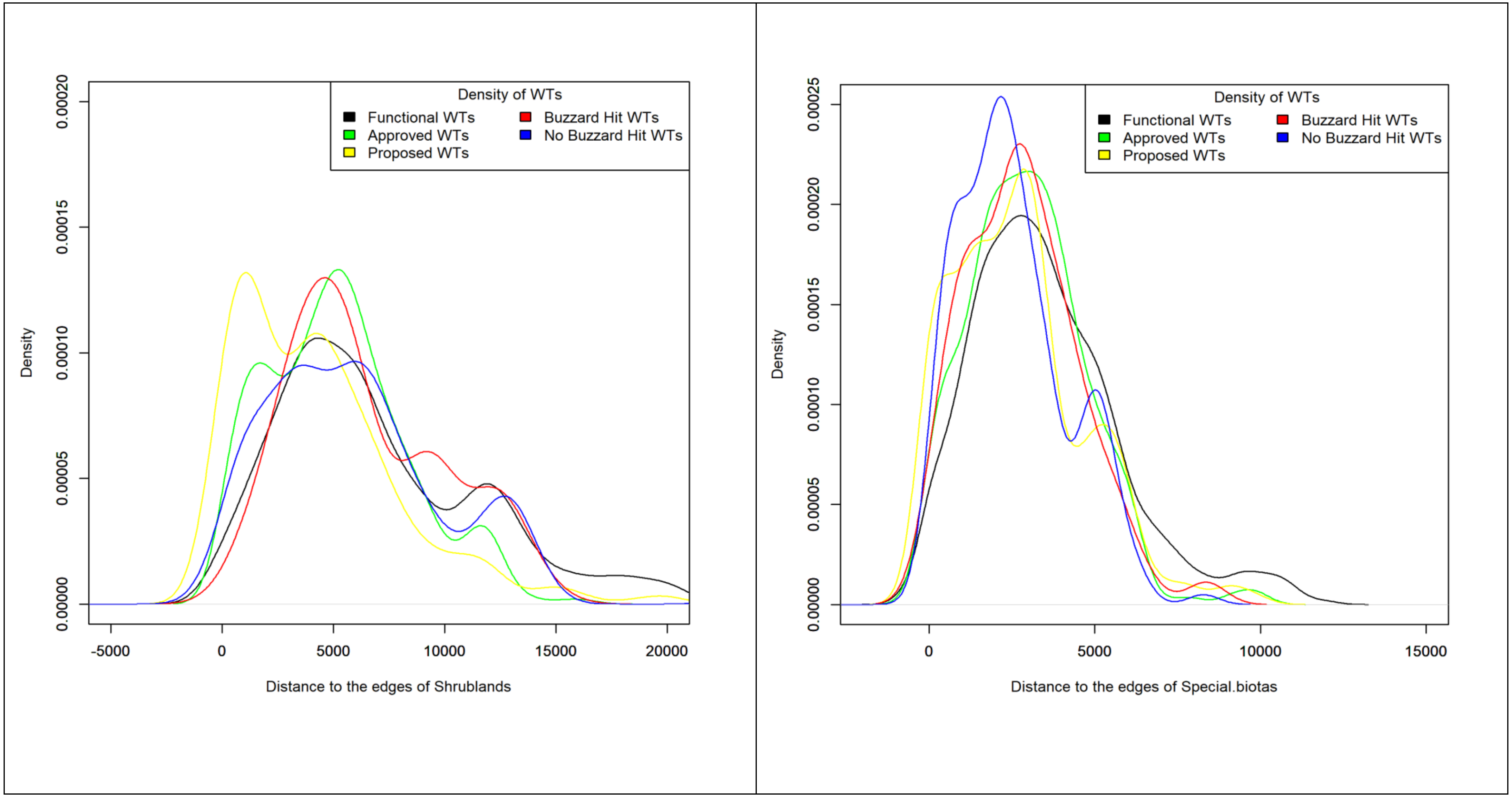
0.0005
0.0010
0.0015
-500
0
500
1000
1500
2000
2500
Distance to the edges of Settlements.and.structures



Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
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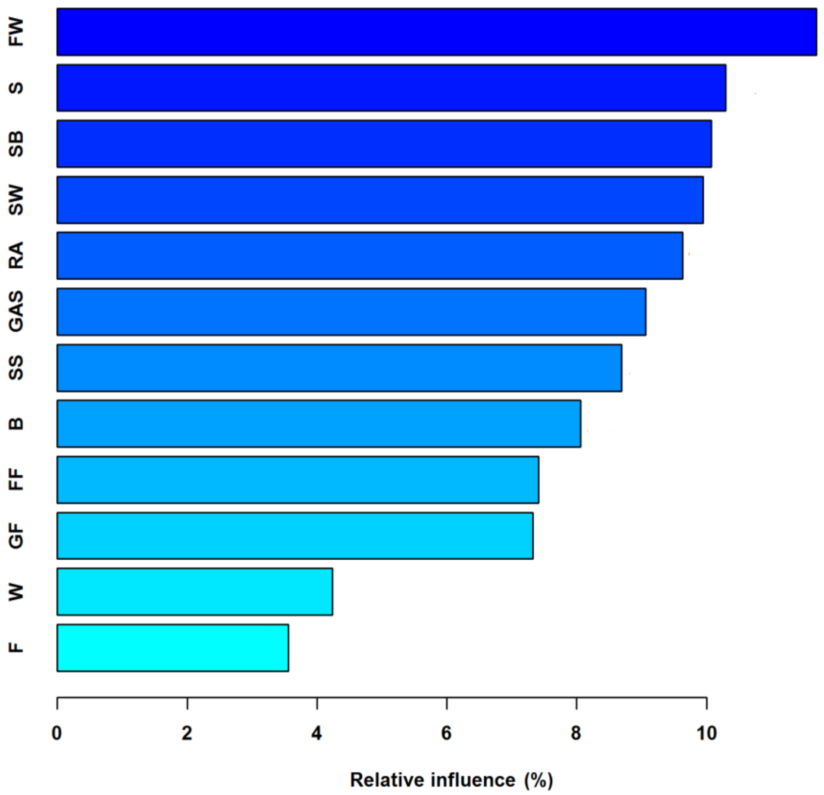
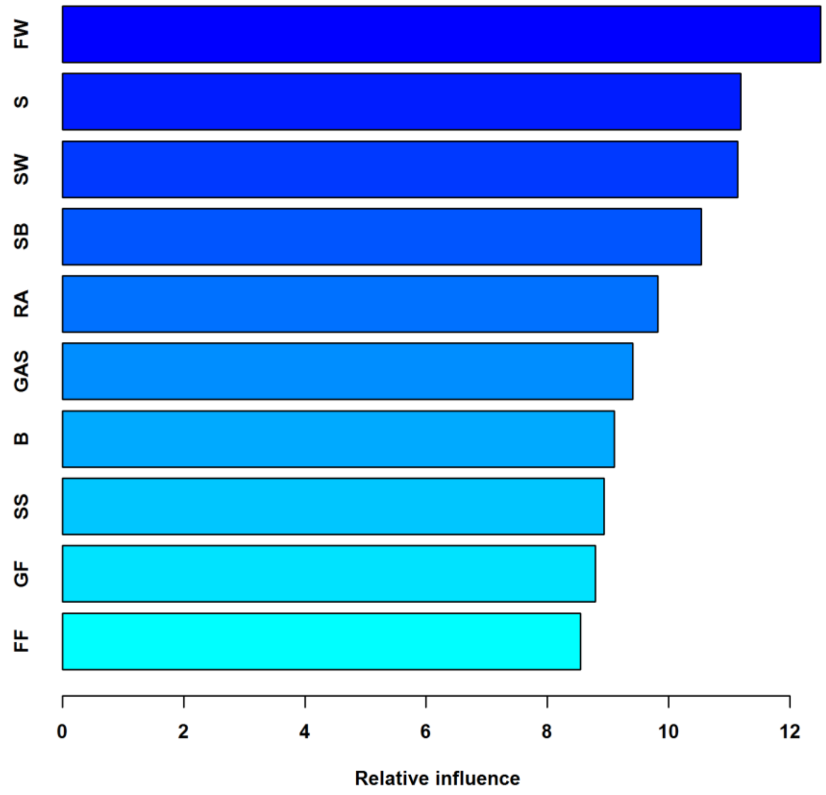
0.00005
0.00010
0.00015
0.00020
-5000
0
5000
10000
15000
20000
Distance to the edges of Shrublands
Density of WTs
Functional WTs
Approved WTs
Proposed WTs
Buzzard Hit WTs
No Buzzard Hit WTs
Density
0.00000
0.00005
0.00010
0.00015
0.00020
0.00025
0
5000
10000
15000
Distance to the edges of Special.biotas

Annex: Figure A10 & A11: The relative contributions (%) of the (DELV) predictor variables for BRT full and simplified models. Developed with cross-validation on data from 332 sites and a tree complexity of 12 and 10 respectively. The full model was fitted with 12 predictors and least contributing 2 were removed and the simplified model was fit with the remaining 10 predictors.





Chapter IX: Publications

PEER-REVIEWED ARTICLES

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2018) Collision sensitive niche profile of the worst affected bird-groups at wind turbine structures in the Federal State of Brandenburg, Germany. Scientific Reports. 8: 3777.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2019) Predicting strike susceptibility and collision patterns of the Common Buzzard (Buteo buteo) at wind turbine structures in the federal state of Brandenburg, Germany. PLOS ONE. 15(1): e0227698.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2020) Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany. Conservation Science and Practice. e199.

CONFERENCE PRESENTATIONS

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2014) Birds & Blades: Creating Bird Friendly Wind Turbines. *German Indian Business Center (GIBC)*, Hannover, Germany. Oral presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2015) Clean Energy, Dead Birds? An attempt to create bird friendly wind turbines across the federal state of Brandenburg, Germany. *Helmholtz Center for Environmental Research: UFZ Energy Days 2015*, Leipzig, Germany. Oral presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2015) Factors promoting avian mortality at wind turbine structures: Insights from long-term avian mortality data in the federal state of Brnadenburg, Germany. *9th IALE World Congress*, Portland, Oregon (USA). Oral presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2015) Birds & Blades: an investigation towards birds and wind turbines spatial coexistence. *Helmholtz Interdisciplinary GRADuate School for Environmental Research (HIGRADE): Fall Conference 2015*, Leipzig, Germany. Poster presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2016) Predicting strike susceptibility and collision patterns of the common buzzard at wind turbine structures in the federal state of Brandenburg, Germany. *46th Annual Meeting of the Ecological Society of Germany, Austria and Switzerland - 150 years of ecology - lessons for the future*, Marburg, Germany. Oral presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2016) Environmentally smart spatial allocation of wind turbine structures. *HUSUM Wind India Conference: Intersolar India Exhibition and Conference 2016*, Mumbai, India. Oral presentation.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2017) Breaking the walls of birds, blades and wind sharing. *Falling Walls Lab India 2017: DWIH - German Centre for Research and Innovation*, Chennai, India. Oral presentation.

PRESS RELEASES

Bose, A., Dürr, T., Klenke, R.A. and Henle, K. (2015) Birds & Blades: Environmentally safe spatial allocation of wind turbine structures. "*Energy–make it bird-friendly!": World Migratory Bird Day 2015.* UN Environment Programme (UNEP)/ The Convention on Migratory Species (CMS)/ Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA).

EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne Verwendung unerlaubter Hilfe angefertigt zu haben. Die aus fremden Quellen direkt oder indirekt übernommenen Inhalte sind als solche kenntlich gemacht. Die Dissertation wird erstmalig und nur an der Humboldt-Universität zu Berlin eingereicht. Weiterhin erkläre ich, nicht bereits einen Doktortitel im Fach Geographie zu besitzen. Die dem Verfahren zu Grunde liegende Promotionsordnung ist mir bekannt.

Anushika Bose

Berlin, den 21. Januar 2021